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14. ABSTRACT
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Final Report

(DURIP) MIMO Radar Testbed for

Waveform Adaptive Sensing Research

Contract/Grant # W911NF-13-1-0280

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Foreword Microwave radar systems are crucial components of any standoff sensor system due to their all-weather capabilities and proven performance for tracking, imaging, and situational awareness. However, complex electromagnetic wave propagation environment such as urban area with clutter discrete can make separation of target signatures and propagation channel effects difficult; a radar capable of adaptively varying its transmit waveforms for probing the environment, including the use of multiple transmit/receive antennas can provide distinct gains in separating these effects.

Under this DURIP program we build a collaborative research resource based on software defined radar (SDR) platforms that can adaptively modify both transmit waveforms and receive signal-processing tasks in real time. This collaborative research resource will be utilized by faculty and students of the Ohio State University, University of Michigan, Massachusetts Institute of Technology and Arizona State University. The testbed consists of 14 Micro SDR Platforms with 2 transmit and 1 receive antennas and a standalone high performance multichannel SDR multiplexed to a 32 x 32 antenna array.

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1 Problem Statement

MIMO radar systems which can transmit independent waveforms on multiple antennas have been suggested for improving detection, parameter estimation and clutter suppression capabilities. While many traditional multi-antenna radar concepts such as phased-array, receive beamforming, STAP, polarimetry, and interferometry can be seen as special cases of MIMO radar, the distinct advantage of a multi-antenna radar system with independent transmit waveforms is the increased number of degrees of freedom leading to improved resolution, detection and parameter estimation. MIMO system benefits can be realized in the form of reduced pulse repetition frequency (PRF), larger spot sizes, and/or lower transmit energy.

In the literature, MIMO radars are distinguished based on the geometry of the receive and transmit centers. There are two main categories. MIMO radars with widely separated transmit and receive arrays provide statistically independent measurements of the illuminated scene and are categorized as a statistical MIMO radars. MIMO radar systems with widely separated antennas employs spatially diverse transmitters and receivers to overcome target fading effects [1], [2] or to estimate a target's location with high resolution [3, 4]. If antennas are relatively close to each other, so that for each scatterer in the illuminated scene the angle of arrival is approximately the same for all phase centers, then the system is referred to as a coherent MIMO radar. The main advantage of the coherent MIMO radar is its ability to synthesize a large virtual array with fewer antenna elements for improved spatial processing. The OSU micro SDR platforms we developed will enable research in both modalities as well as novel hybrid modes combining elements of the two in a multi-static setting.

In this project our focus is development of a low power, short range versatile radar system that combines a high speed FPGA digital back-end with sideband digital/analog and analog/digital converters with a custom built RF Frontend. The key idea is software defined radar system is to sample the transmit/receive waveforms using high speed digital/analog and analog/digital converters and to implement key processing stages using programmable digital hardware [5]. This allows the SDR to, for example, change modes from detection to tracking, or adapt its waveform based on environmental conditions and or information derived from previous radar interrogations. Increasing number of transmit and receive channels with the use of antenna switching matrix for MIMO applications is discussed in [6]. The use of MIMO radar for studying wideband radar array signal processing in short range indoor application has been demonstrated in [7], where non-adaptive linear frequency FM waveforms are used. Application of waveform adaptation for matching transmitted waveform to the target's impulse response improves target detection and aids in target identification [8, 9]. However, experimental verification of these ideas have not been widely explored.

Under this DURIP program we build a collaborative research resource based on software defined radar (SDR) platforms that can adaptively modify both transmit waveforms and receive signal-processing tasks in real time. The testbed consists of 14 Micro SDR Platforms with 2 transmit and 1 receive antennas and a standalone high performance multichannel SDR multiplexed to a 32 x 32 antenna array. This two-tiered architecture allows research and experimentation in many domains of active sensing. Specifically we focus on three scenarios:

- Micro SDRs can be deployed to perform non-coherent fusion of backscatter returns (also known as statistical MIMO radar) to decrease fluctuations in target returns to selective fading through spatial diversity. The Micro SDRs can modify their transmit waveforms and pulse repetition frequencies cooperatively to adapt changes in the background and target returns as well as scene complexity. In addition micro SDRs can be mounted on robotic platforms to optimize the collection geometry and derive fusion research with other modalities such as

EO, IR cameras and acoustic sensors.

- Co-located MIMO array paired with the switchable antenna array matrix can emulate airborne collections with its 32x32 antenna matrix. Focus will be on space-time adaptive (STAP) techniques for detection of slow moving targets against stationary clutter. Specifically, the performance of the MIMO STAP techniques critically hinges on the structure of the clutter covariance matrix, and to our best knowledge the testbed will be unique in its data collection capability for massive MIMO arrays.
- Alternatively the two components of the testbed can be combined to provide a novel operation scenario, where the coherent MIMO array is used to emulate illumination by an airborne platform with multi-static passive sensing by micro-SDR platforms from diverse set of aspect angles.

There are many other scenarios where the components of the testbed can be used to derive research in active sensing. This report focuses on details of the hardware design for the SDR platforms.

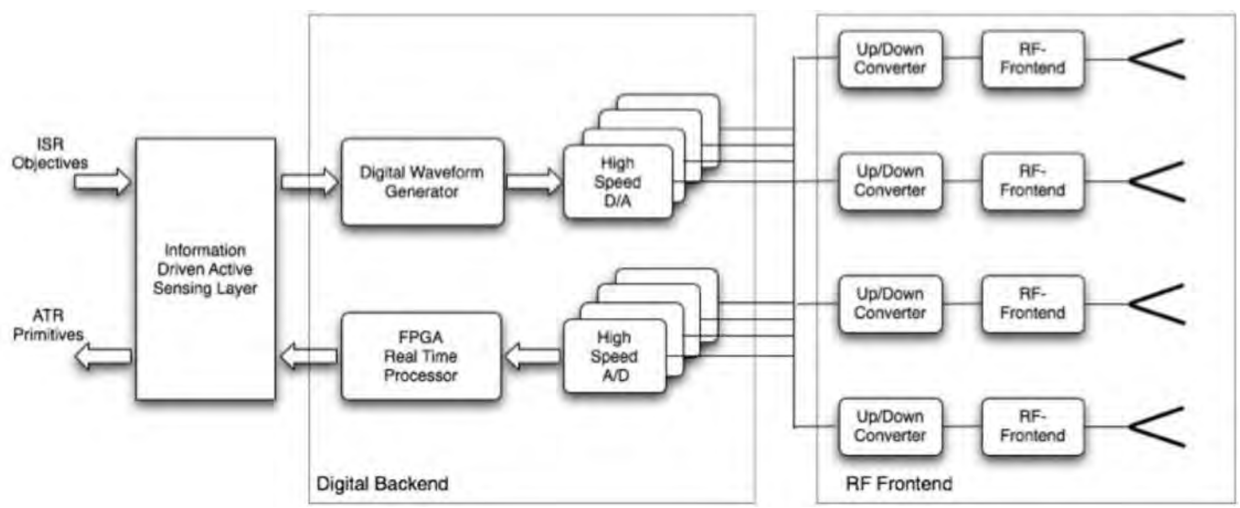


Figure 1: Waveform adaptive MIMO SDR

2 Design Summary and Results

The operational principle of a software defined radar system is to sample the transmit/receive waveforms using high speed digital/analog and analog/digital converters and to implement key processing stages using programmable digital hardware. The block diagram for the proposed software defined radar system is given in Figure 1. A high speed digital waveform generator is used to construct independent waveforms for a set of transmit antennas, and produces a synchronized multi-channel baseband transmit signal which is mixed and amplified for transmission. In the receive signal chain, the received energy is filtered, amplified, and downconverted by an RF module, sampled in the baseband bandwidth synchronously across the multiple channels, and passed to an FPGA-based real-time signal processor for multi-channel coherent processing. The adaptive operation of the system is controlled by the information driven active sensing layer which allocates system resources to achieve sensing objectives by supplying the user with ATR primitives (target detections, target track and ID). The current implementation of the micro SDR platform is given in Figure 2 with the custom X-Band RF frontend developed at OSU on the top and the off the shelf high speed digital backend at the bottom. Design details for the first spiral of the design cycle were reported earlier in [10].

Figure 2: OSU Micro SDR platform

2.1 Novel Hybrid Up and Downconversion Stage Design

In an idealized model of software defined radar analog-to-digital and digital-to-analog conversion will be accomplished at the RF frequency band without analog conversion stages. This way, down and up-conversion will be performed in the digital domain limiting the analog components to high-dynamic range low noise amplifier (LNA) and power transmit amplifiers. Unfortunately, existing ADC performance is far from operating with high dynamic range in the radar bands of interest at multiple GHz. In addition, real time signal processing tasks of frequency conversion, digital filtering will require multiple FPGA/DSPs operating on interleaved data to cope with the large sampling rate of receive and transmit signals. Therefore, RF fronted in a software defined radar system have to include up and down conversion stages. There are many options of implementing conversion stages. The most common architecture is heterodyne receiver structure that uses an conversion stages at multiple intermediate frequencies (IF) to implement image suppression and channel selection. Heterodyne receivers can achieve high sensitivity and channel selectivity, DC offset is eliminated in the bandpass filters following each IF conversion. However, large number of components including image rejection filters are required for multiple conversion stages increasing the complexity of the design. At the other end of the spectrum of the receiver structures are Zero-IF receivers that employ single quadrature demodulator to bring the RF passband signal to complex baseband. Zero-IF receivers are not subject to the image problem common to receivers with intermediate frequency conversion stages. However, significant DC offsets at the output of quadrature mixers as a result of LO leakage signal mixing with itself.

In our design we employ a hybrid structure relying on the oversampling design of the DAC which can generate waveforms at digitally generated IF frequencies. On transmit, we directly generate a pass band signal around a lowIF frequency of 187.5 MHz with a bandwidth of 125 MHz using the oversampling DACs in our system. Each DAC is used to generate an independent transmit waveform as real-valued pass band signal. For each transmit channel, low-IF pass-band signal is up-converted to X-band using a single channel mixer. We use a RF pass-band filter to reject the image and LO leakage. On receive we use a RF band-pass filter to limit the wideband noise and a zero-IF receiver with quadrature downconversion with the same LO that generated the transmit signal. As a result the received signal is passband signal at the output of down-conversion mixer's I and Q outputs. Next, we employ standard bandpass sampling in the second Nyquist zone, to alias the digitally generated low-IF signal to the baseband. We note that in our system DAC and ADC use a single clock -source eliminating the problem of clock-jitter limiting the performance of band-pass sampling systems in practice. In addition low-IF bandpass sampling system enables us to use a DC-blocker at the output of quadrature mixer output, eliminating the DC-offset problem common to zero-IF receivers. Figure 3 shows the novel hybrid up and downconversion employed in our design

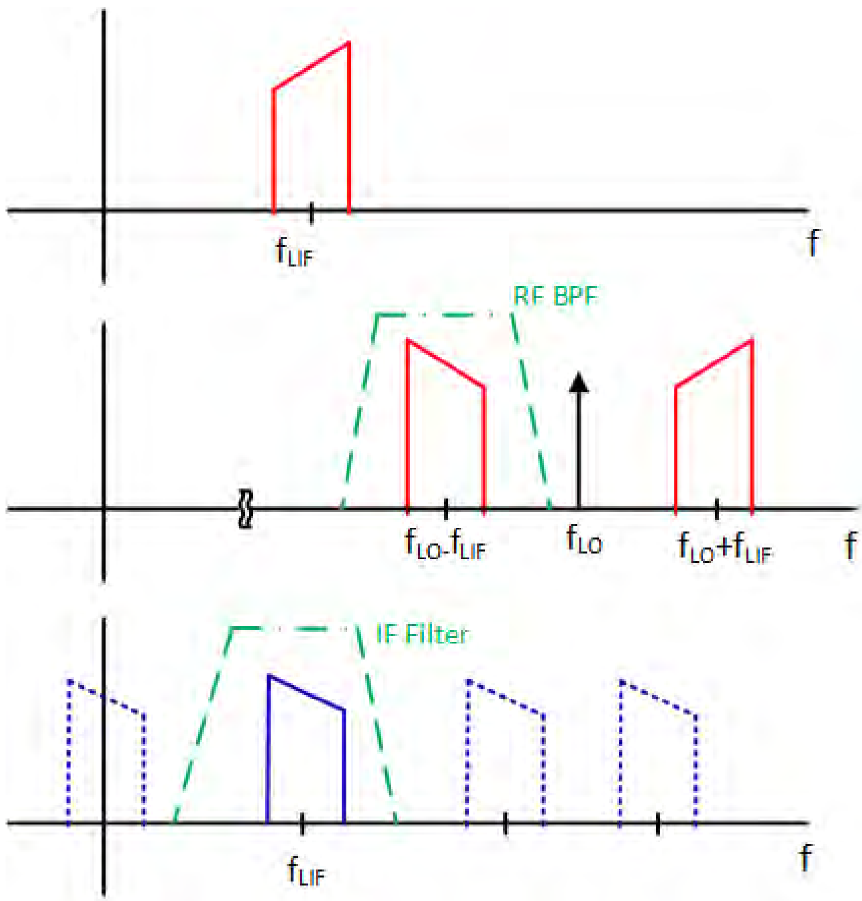


Figure 3: Frequency content of the transmit baseband, transmit passband and receive baseband signals. Bandpass sampling aliasing is depicted as dashed lines.

The custom RF Frontend built at Ohio State features two independent Transmit (TX) and a single Receive (RX) channel multiplexed to four receive antennas. The instantaneous bandwidth of the system is 250 MHz. The RF Frontend operates at X-band and includes an onboard Phase Locked Loop (PLL) and Voltage Controlled Oscillator (VCO) to generate Local Oscillator (LO) signal from a local GPS conditioned oven-controlled 10 MHz reference.

2.2 RF Frontend Design

Figure 4 shows the block diagram of Receiver. The inputs of four RX antennas are fed to a Low Noise Amplifier (LNA) whose output is connected to receive frontend through switching circuit. Since it is likely that the antennas will be connected to the rest of the RF system by long cables, including the LNA close to the antenna reduces the impact

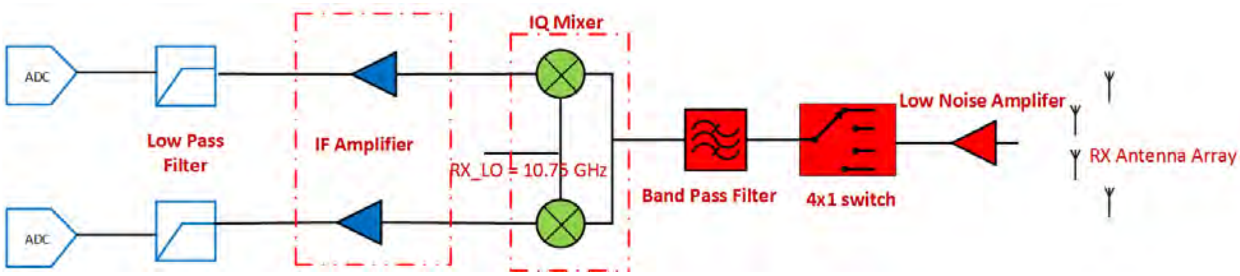


Figure 4: Block Diagram of receiver

of cable loss on receiver's overall noise figure. The signal from the switch is filtered through a resonant coupled Band Pass Filter (BPF) to filter any blocker and image signal. The filtered signal is down converted by In-phase and Quadrature (IQ) mixer and the down converted signal is amplified by an IF amplifier. The amplified signal is filtered by a low pass filter and digitized by high speed ADC. In order to minimize the phase and amplitude imbalance in IQ signal, the I and Q channels are routed symmetrically and dual IF amplifier is used for amplification.

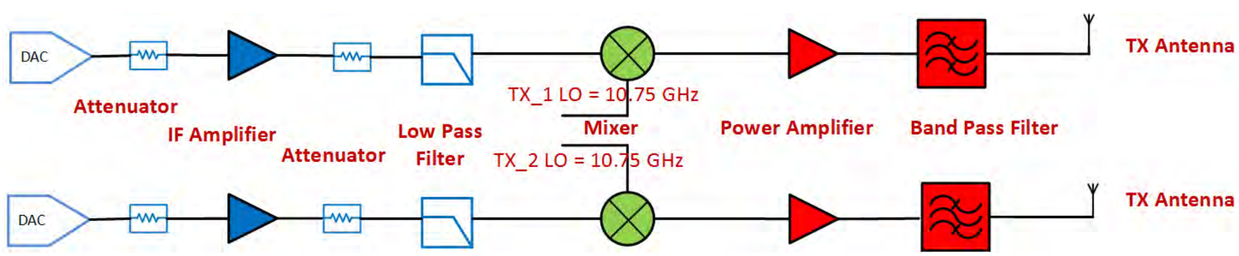


Figure 5: Block Diagram of Transmitter

Figure 5 shows the block diagram of Transmitter. The IF signal is generated by the DAC at 250 MHz and 0 dBm power. The IF single is filtered by a Low Pass Filter (LPF) to remove digital copies and amplified by a base band amplifier. The amplified signal is up converted to X-Band using a double-balanced mixer and further amplified by a high Power Amplifier (PA). The amplified signal is filtered by a resonant coupled band pass filter to remove mixer and power amplifier inter-modulation components.

The on board PLL requires a reference signal of 50 MHz signal for locking, however the GPS conditioned reference is designed to generate a 10 MHz signal. Hence a 5X frequency multiplier is used and a combination of Low Pass and High Pass filters were used to remove harmonics from the multiplier. The reference signal is further amplifier to compensate for the loss during frequency multiplication. This resulting 50 MHz signal is used as reference by the

PLL. Output of PLL is divided equally by a 3 dB splitter and further amplified by driver amplifiers and this amplified signal is used by the mixers for up and down conversion. The PLL used on the SDR works with a standard four wire Serial Peripheral Interface (SPI). MSP430F1611 micro controller is used for configuring the registers on the PLL upon power up.

Figure 6: Momentum 3D view of Resonant Coupled Band Pass filter

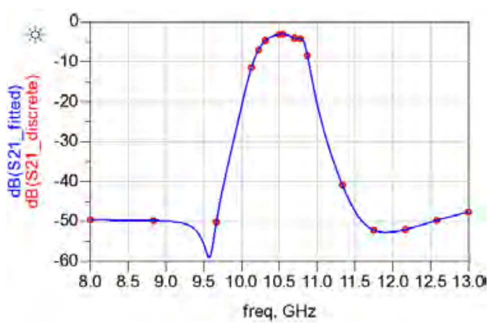


Figure 7: Simulated frequency response of band pass filter

Figure 6 shows the Momentum 3D view of resonant coupled band pass filter used on both transmit and receive section of Ohio State's RF Frontend. Increasing the number of sections will provide a sharper cutoff for the filter but at the same time increase the insertion loss. Hence to optimize both roll off and insertion loss a four section topology was chosen. Each section of the filter is designed with Microstrip coupled line (MCLIN) and Linecalc software was used to calculate odd and even mode impedance of MCLIN. Microstip to Coplanar Waveguide (CPW) transition was designed and added to both input and output ports of the filter so that the filter can be connected to the components on the board. Figure 7 shows the frequency response of the filter. From the figure it can be seen that the insertion loss at center frequency is roughly 3 dB and attenuation at the sideband ($F_{LO} + F_{IF}$) is approximately 20 dB.

Schematics and the layout of the RF Frontend Printed Circuit Board (PCB) designed at Ohio State are given in Appendix A. All the RF and IF components are placed on the top side of the board. To minimize the signal cross coupling and to reduce the effect of power supply induced signal distortion, each RF and IF components have different

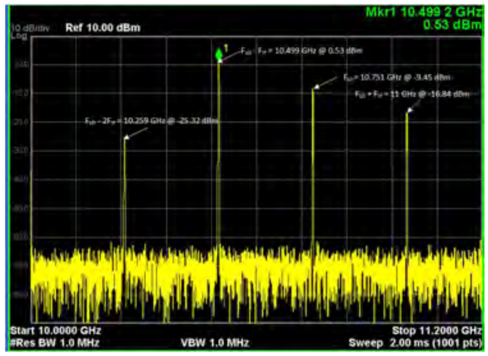


Figure 8: Spectrum of Transmitter with 250 MHz IF signal at -3 dbm power

bias and power supply. The RF Frontend is fabricated on a 4 layer RO4350B substrate and all the RF traces were designed and simulated on Advanced Design System (ADS) software. The board was designed using Allegro PCB editor software.

2.3 Antenna Switching Matrix

Both the micro SDR and standalone multi-channel MIMO SDR unit RF fronted units are designed for interfacing with antenna arrays for multiplexing large number of receive and antenna arrays. For the standalone array we have designed a 32 TX and 32 RX antenna array to interface to 4 transmit and 4 receive channels on the RF frontend. 32 Tx and 32 Rx antennas are printed on a circuit board in two rows parallel to each other. The system can emulate linear airborne motion along its long axis by sequentially selecting 4 consecutive Rx antennas out of the available 32 receive and transmit antennas. For each pulse four independent waveforms are transmitted from four transmitters and received by four antennas that are electronically selected. At subsequent pulses, waveforms transmitted from different set of four receiving and transmit antennas shifted spatially $k\lambda/2$ relative to the previous set, where λ is the wavelength and k is an integer.

The emulated airborne speed is given by the spacing between elements of the synthesized receivers arrays in subsequent pulses and the pulse repetition frequency. Each receive antenna has an LNA mounted on the back to minimize the noise figure. Then we use set of four 4×1 switches followed by another 4×1 switch to allow routing of 32 antennas to the 4 physical channels on the fronted. Schematics for the switching matrix are given in Appendix B.

2.4 Benchtop Measurements

All measurements were performed in lab environment with IF signal generated with Agilent Analog Signal generator and measured with Agilent PXA Spectrum Analyzer. The receiver is characterized with transmit signal looped back to receiver with 40 dB attenuation. Figure 8 shows the transmit spectrum with 250 MHz signal at IF. The desired signal appears at $(F_{LO} - F_{IF})$. Along with the desired signal, LO signal is also present due to the finite LO-RF isolation of the mixer. However on the receiver side, during down conversion this LO leakage signal will be down converted to Direct Current (DC) and will be blocked by capacitors. In addition to this $F_{LO} + F_{IF}$ and $F_{LO} - 2F_{IF}$ (third order inter-modulation) are present at the output. The highest interfering signal is the LO leakage with 10dB suppression

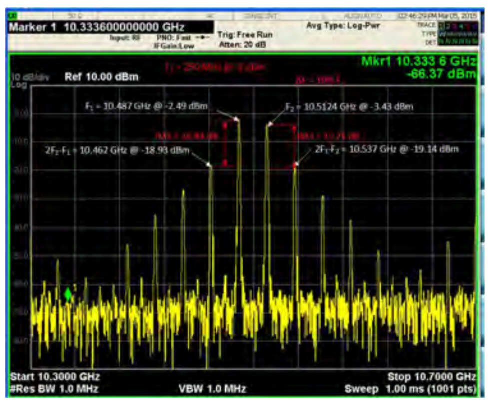


Figure 9: Transmitter Two Tone test result (tones centered at 250 MHz with 25 MHz frequency separation)

Figure 9 shows two tone test result of transmitter. The two tones are -3 dBm in power and are centered at 250 MHz and with 25 MHz separation between them. As seen in any upconversion transmitter, due to the non linearity of mixer and power amplifiers, the two tones interact with each other and produce second and third order inter-modulation products. The important component for signal analysis is third order intermodulation products. From the figure the third order inter modulation products are at $2F_2 - F_1$ and $2F_1 - F_2$. Measured IM3 value is 16.44 dB which is consistent with the theoretical value calculated from specification of the components.

Table 1 summarizes measured critical performance metrics of the Transmitter and Receiver.

Table 1: Critical Specifications of Transmitter and Receiver

Specification	**Transmitter**	**Receiver**
Gain	23.40 dB	24.20 dB
OIP3	33.99 dBm	29.20 dBm
P1dB	-0.30 dBm	-7.82 dBm
Noise Figure	NA	2.76 dB

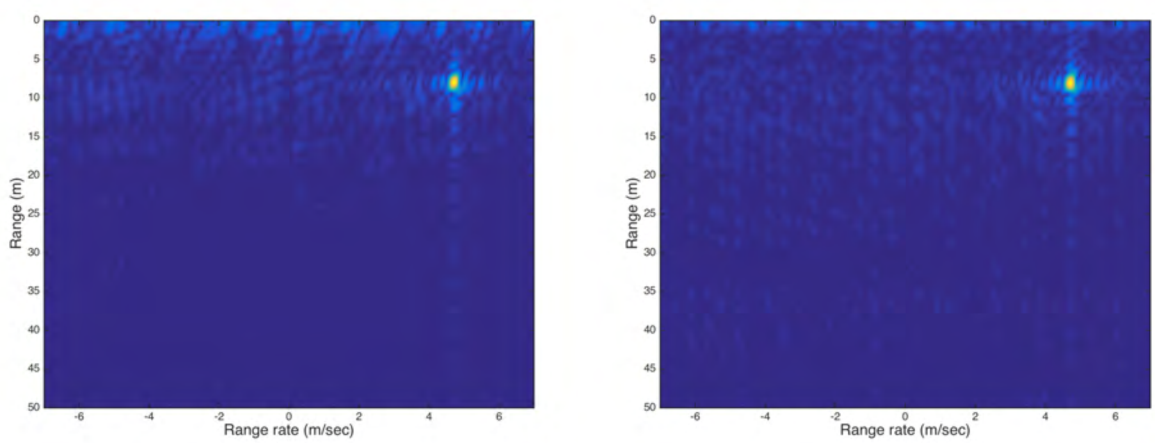


Figure 10: Range-Doppler Map of a vehicle for the two transmit channels

2.5 Experimental Results

We have validated the micro SDR platform performance through field tests. For the particular field test we have used two independent waveforms of 120 MHz Bandwidth: one up-chirp and one down-chirp on the two transmit antennas. The two waveforms are generated coherently in the FPGA and therefore orthogonal at each time in the frequency domain. The backscatter energy from the objects in the field of view are sampled using a single receive channel operating at 250 MSamples/sec at I and Q channels. After baseband filtering and down-sampling the responses to each transmit channel is captured through match filtering with its associated waveform. We use a pulse repetition

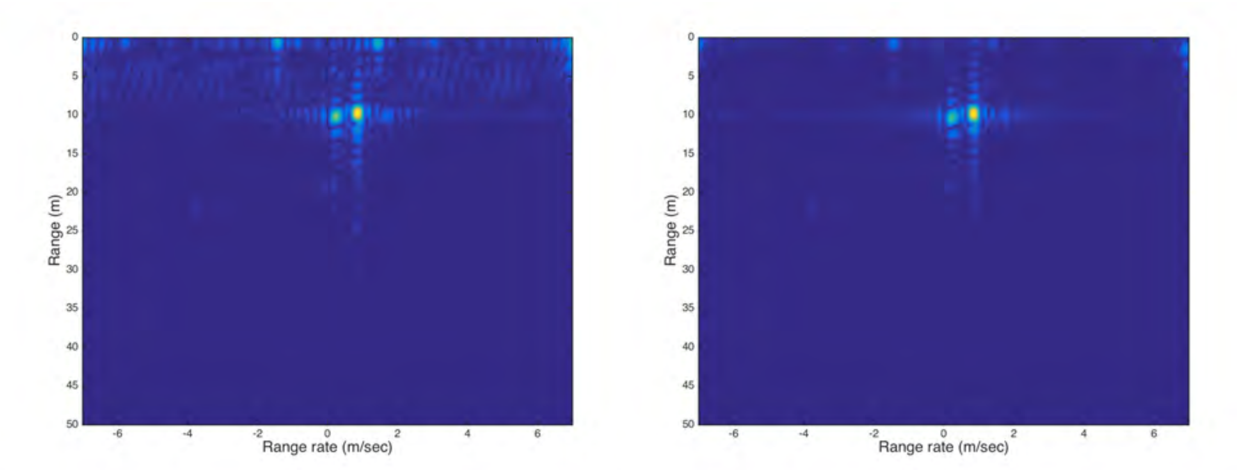
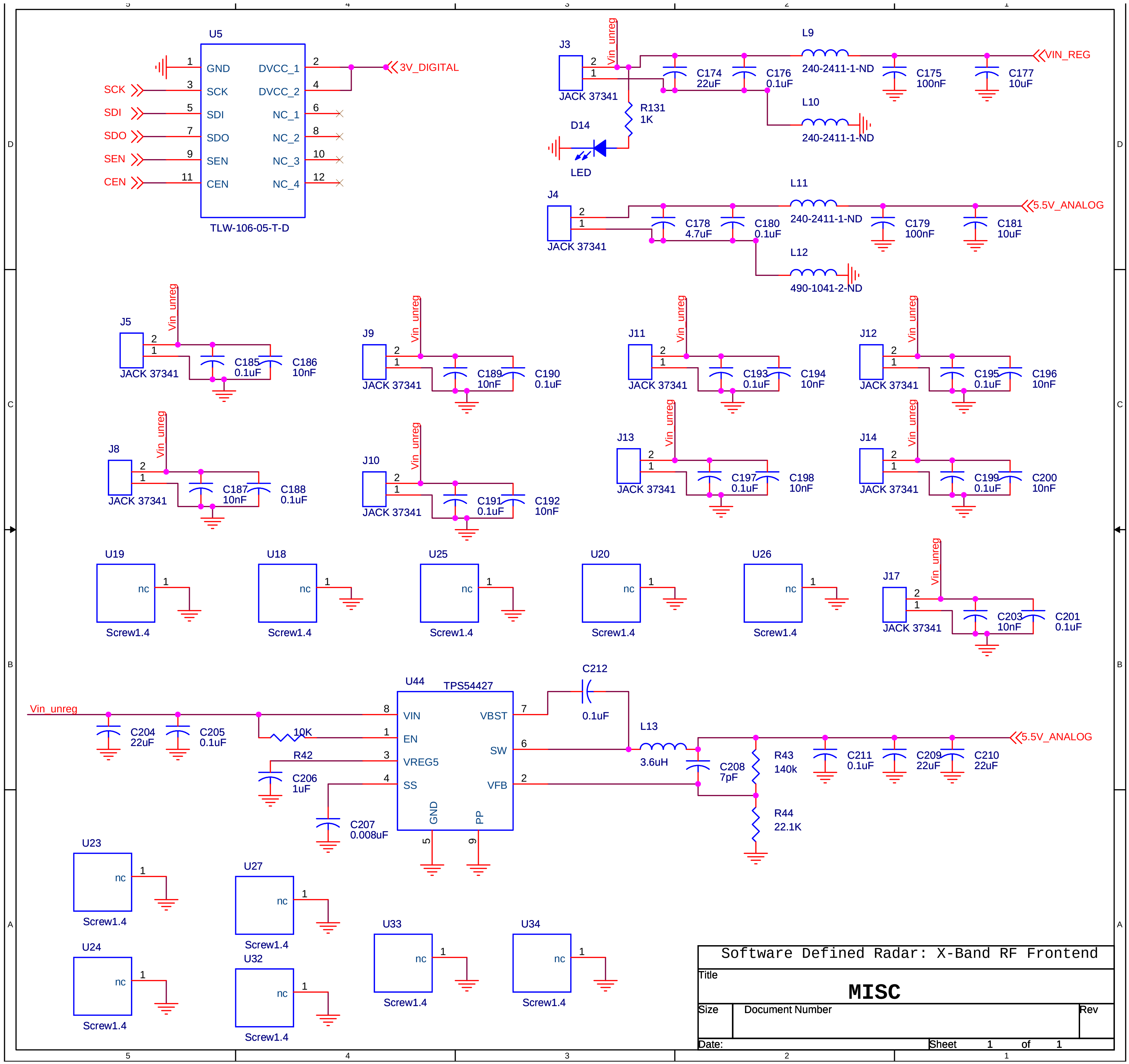


Figure 11: Range-Doppler Map of two dismounts walking at different speeds for the two transmit channels

frequency of 1KHz and use pulses that are 100 μsec long. The coherent processing interval (CPI) Is 64 pulses. The returns are filtered in Doppler to suppress returns form stationary clutter.

In the first experiment returns from a vehicle moving away from the radar are captured. The Range-Doppler map for the two transmit channels captured through a single channel are given in Figure 10. The target returns are clearly visible and show symmetry in the two channels. In the second experiment we have two human subjects moving away from the antenna at different speeds and roughly at the same range of about 10 meters. The Range-Doppler map of the two transmit channels are given in Figure 11. Again the target returns are clearly visible and separated in Doppler.

Appendix A Schematics for X-Band Custom RF Frontend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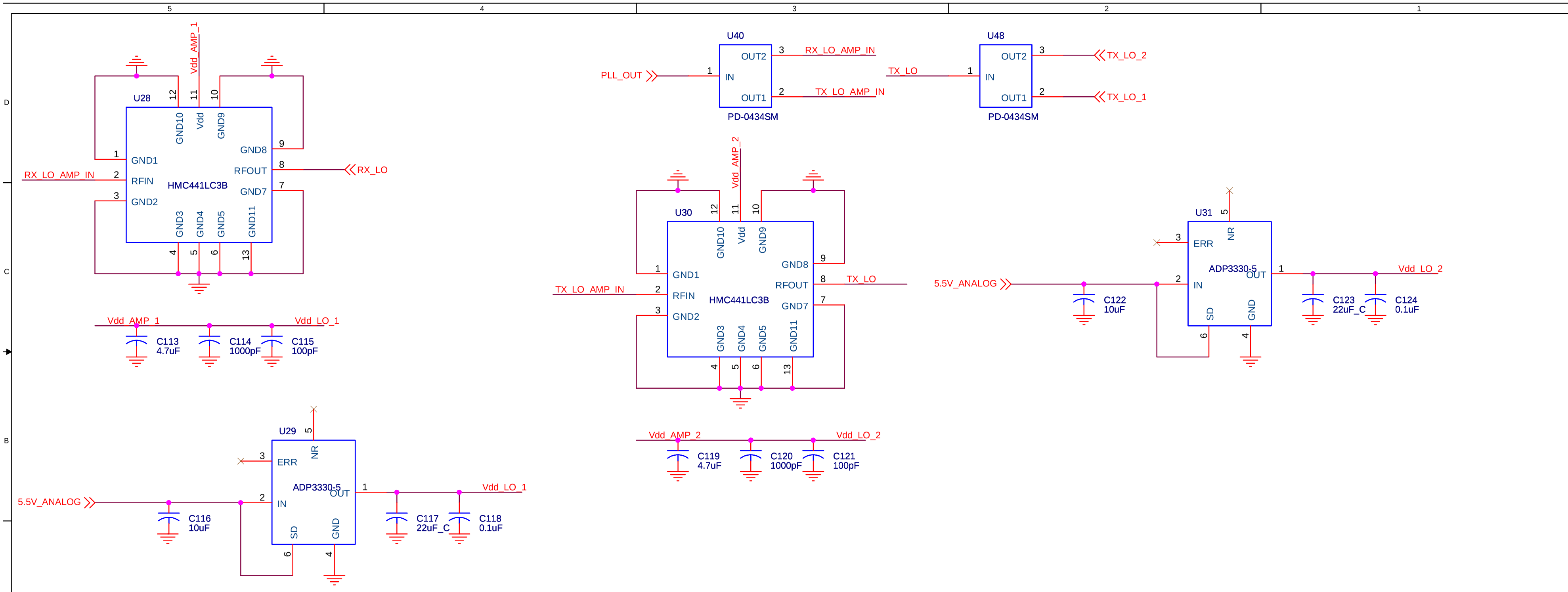


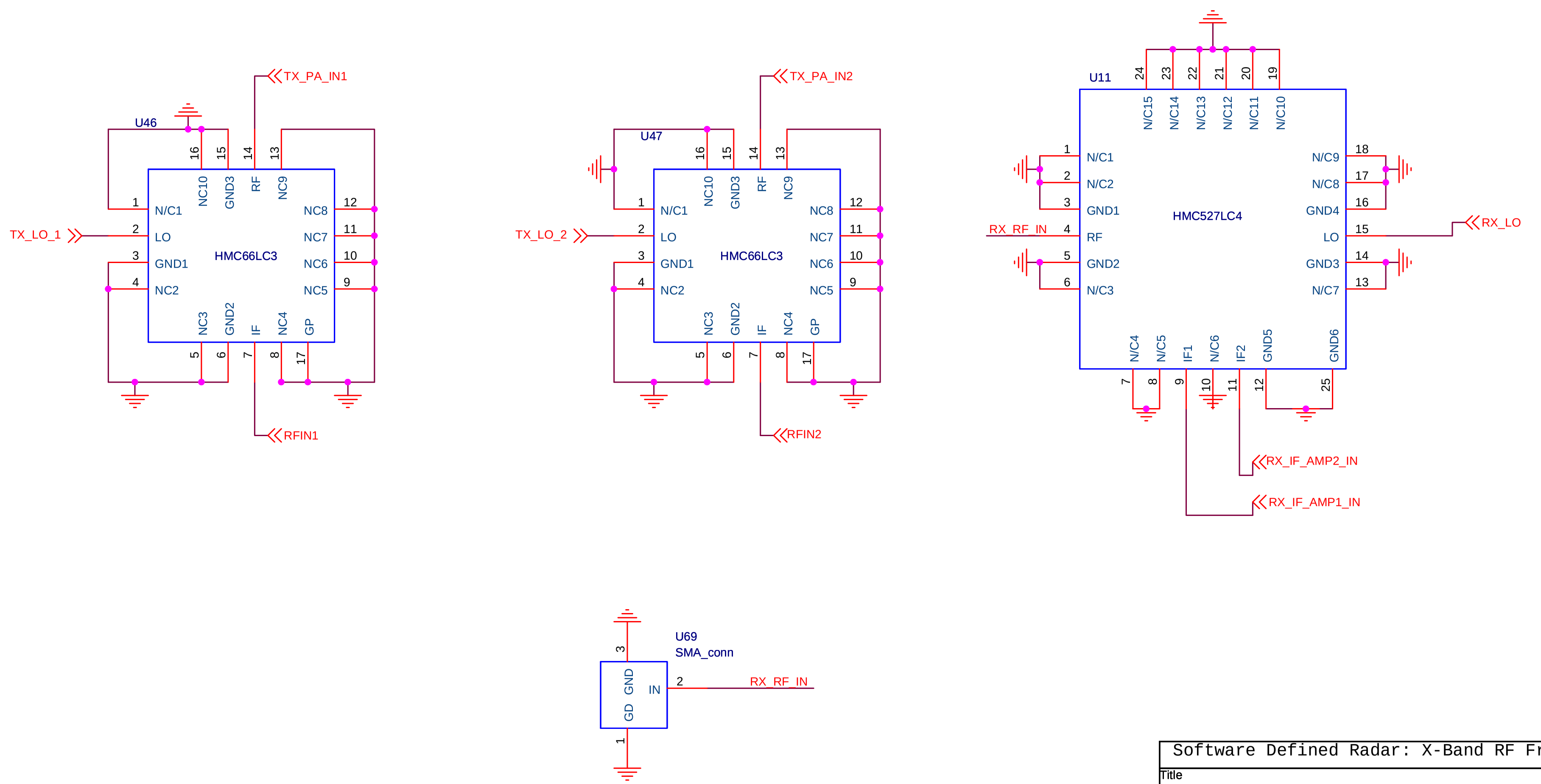
Software Defined Radar: X-Band RF Frontend

Title

TX-RX LO Drivers

Size | Document Number | Rev

Date: | Sheet 1 of 1



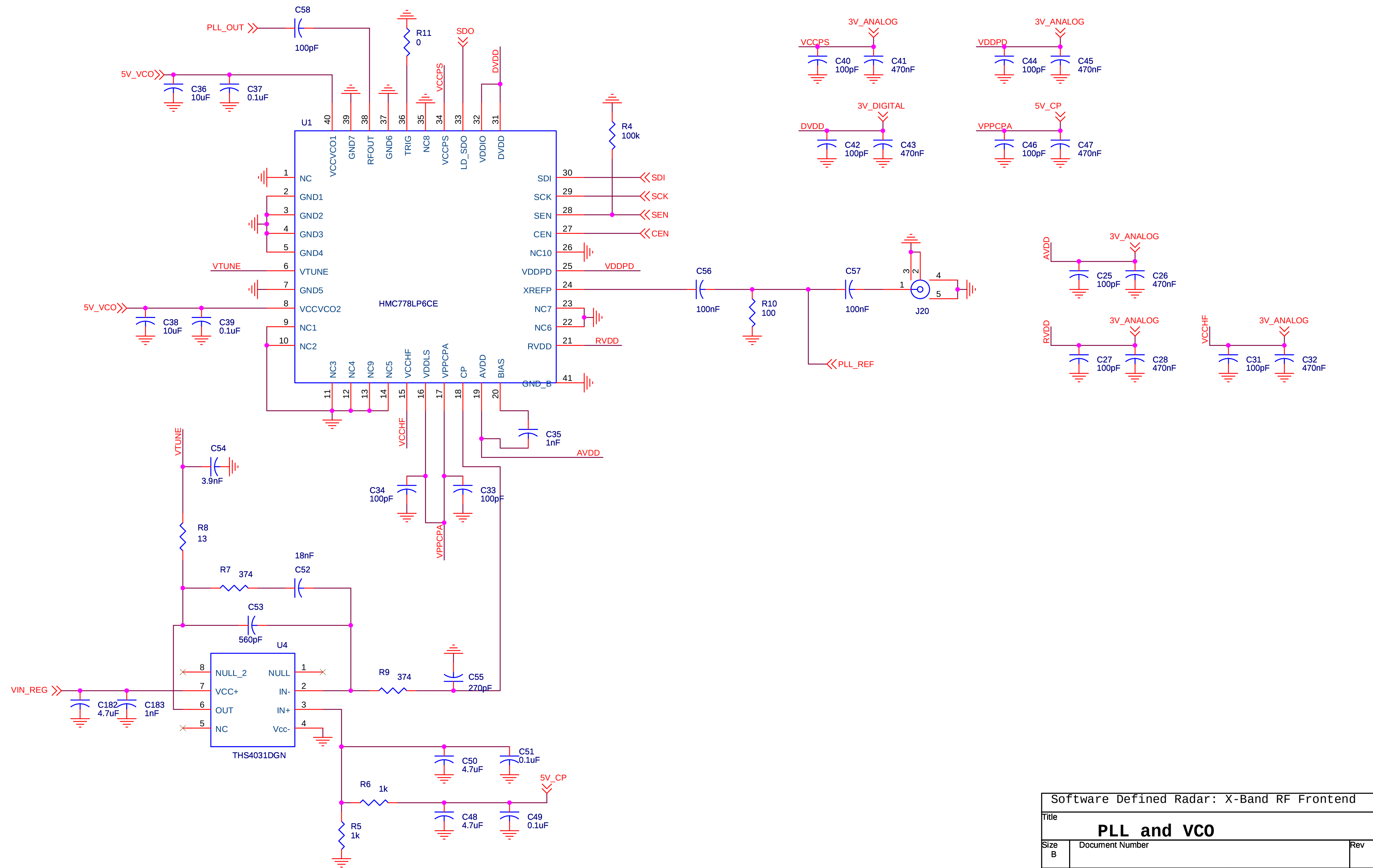
Software Defined Radar: X-Band RF Frontend

Title

TX and RX Mixer

Size	Document Number	Rev

Date: Sheet 1 of 1



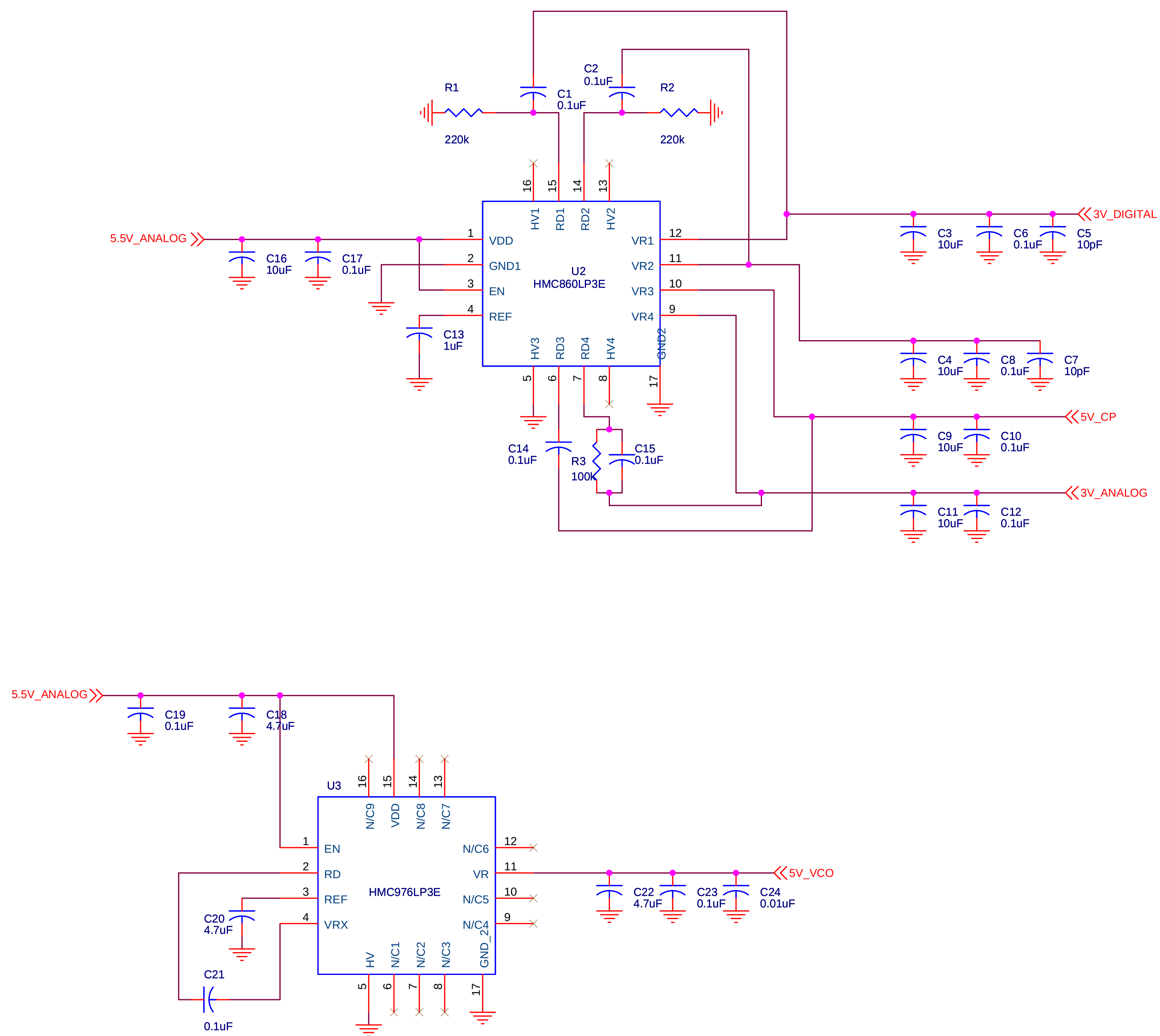
Software Defined Radar: X-Band RF Frontend

Title

PLL and VCO

Size	Document Number	Rev
B		

Date: Sheet 1 of 1

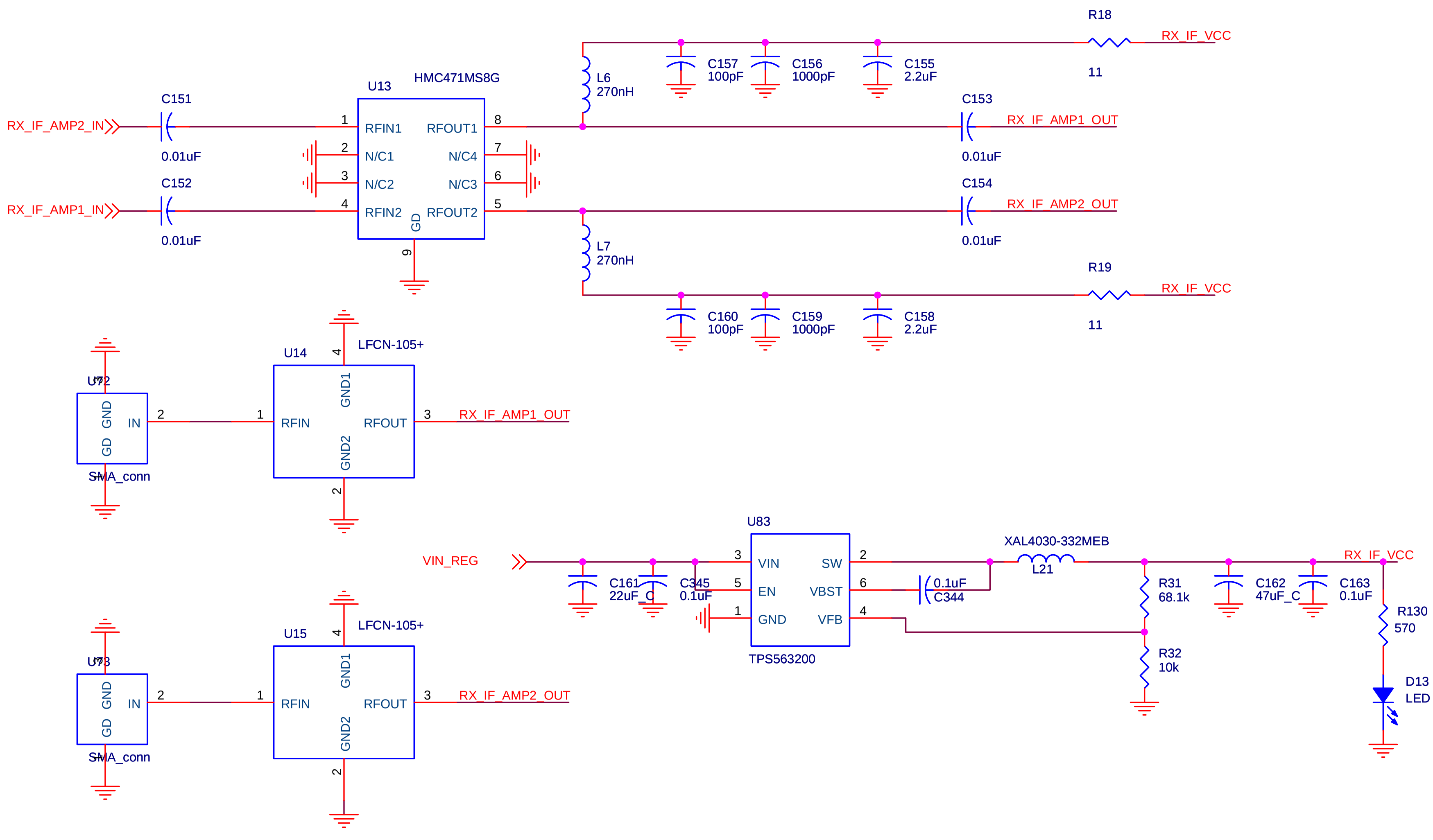


Software Defined Radar: X-Band RF Frontend

Title

PLL and VCO Bias

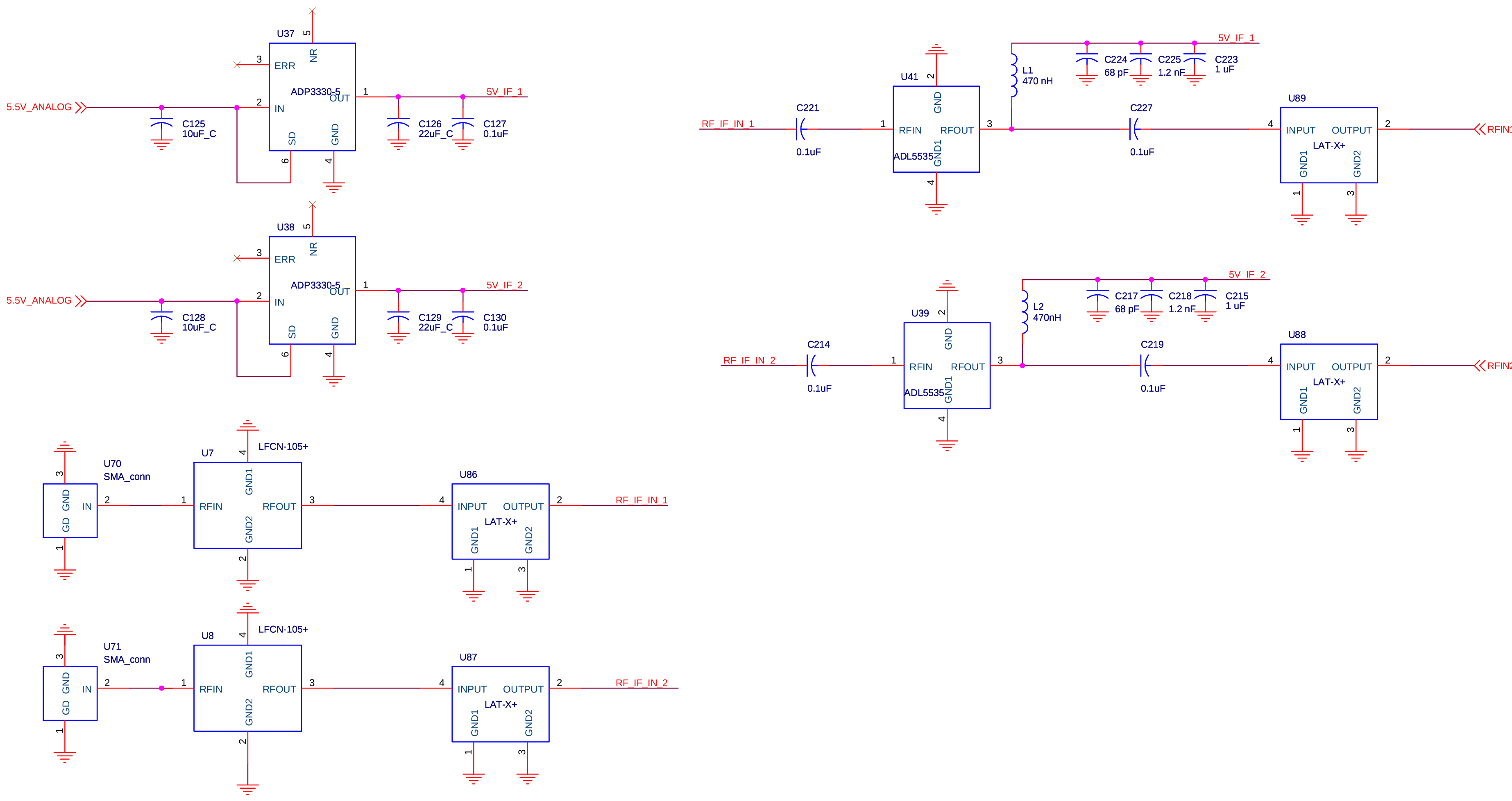
Size	Document Number	Rev
Date:	Sheet 1 of 1	



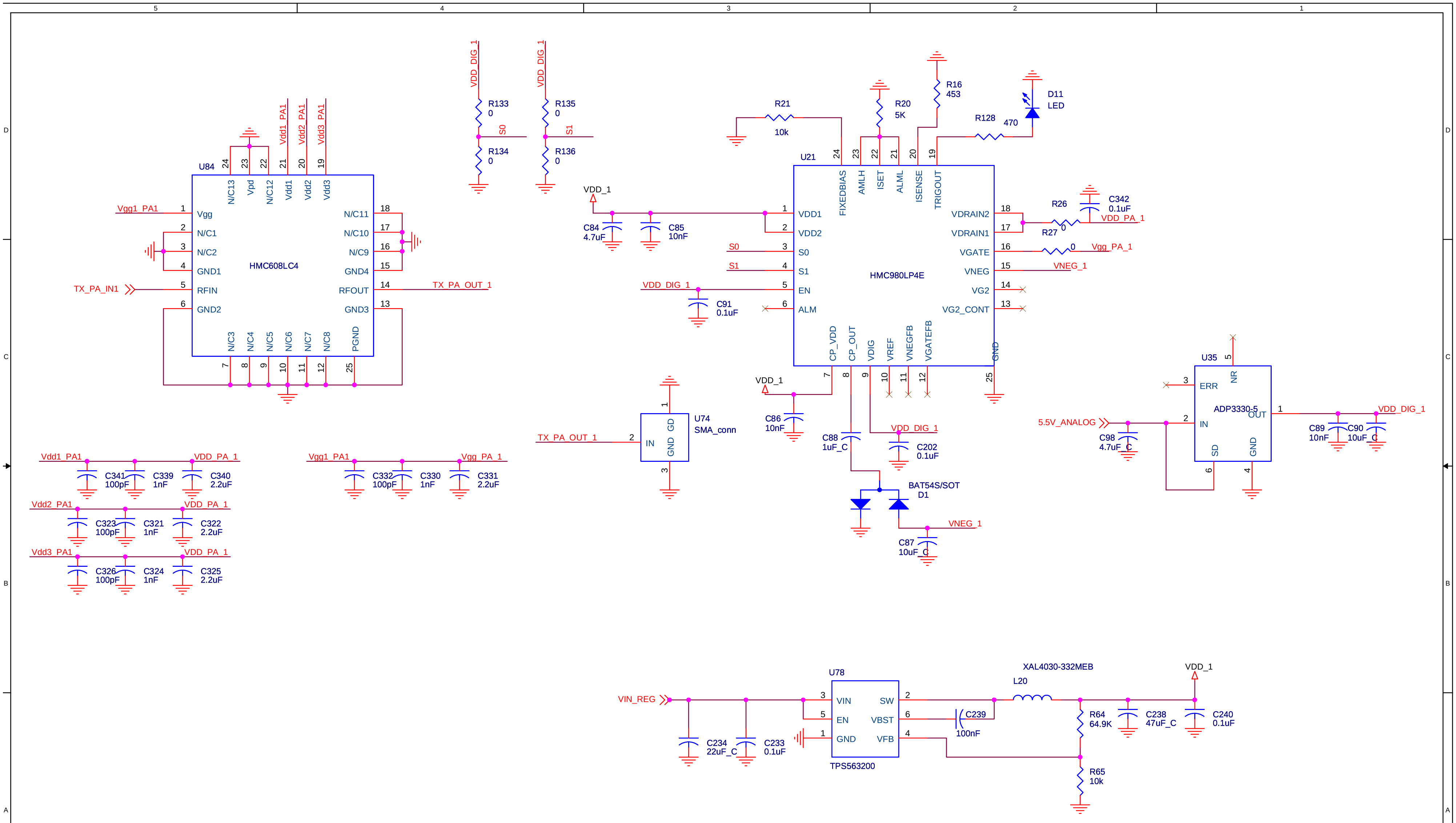
Software Defined Radar: X-Band RF Frontend

Title
Receiver IF Amplifier

Size	Document Number	Rev
Date:	Sheet 1 of 1	



Software Defined Radar: X-Band RF Frontend		
Title: **Transmit IF Amplifier**		
Size: B	Document Number	Rev
Date:	Sheet 1 of 1	

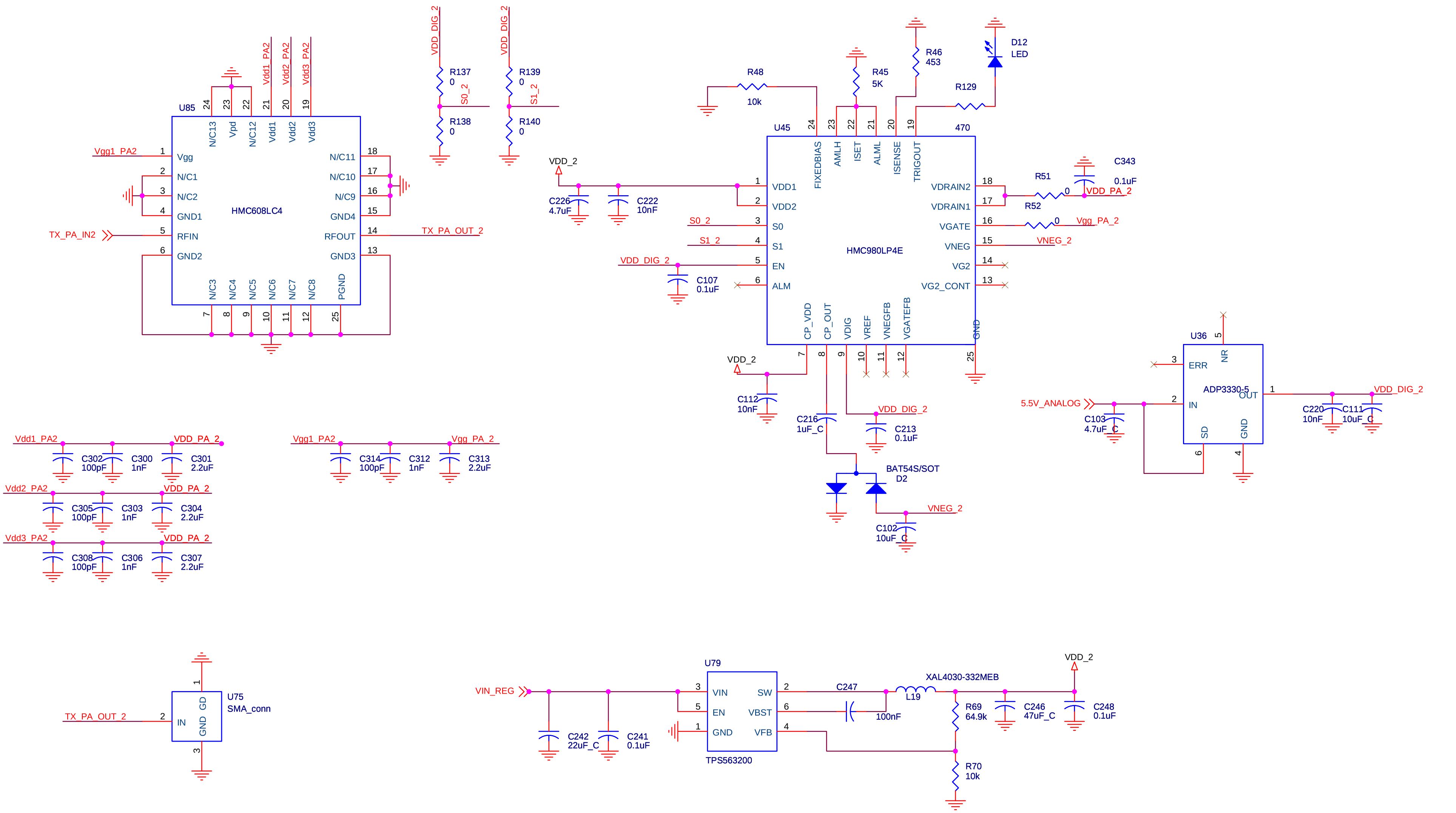


Software Defined Radar: X-Band RF Frontend

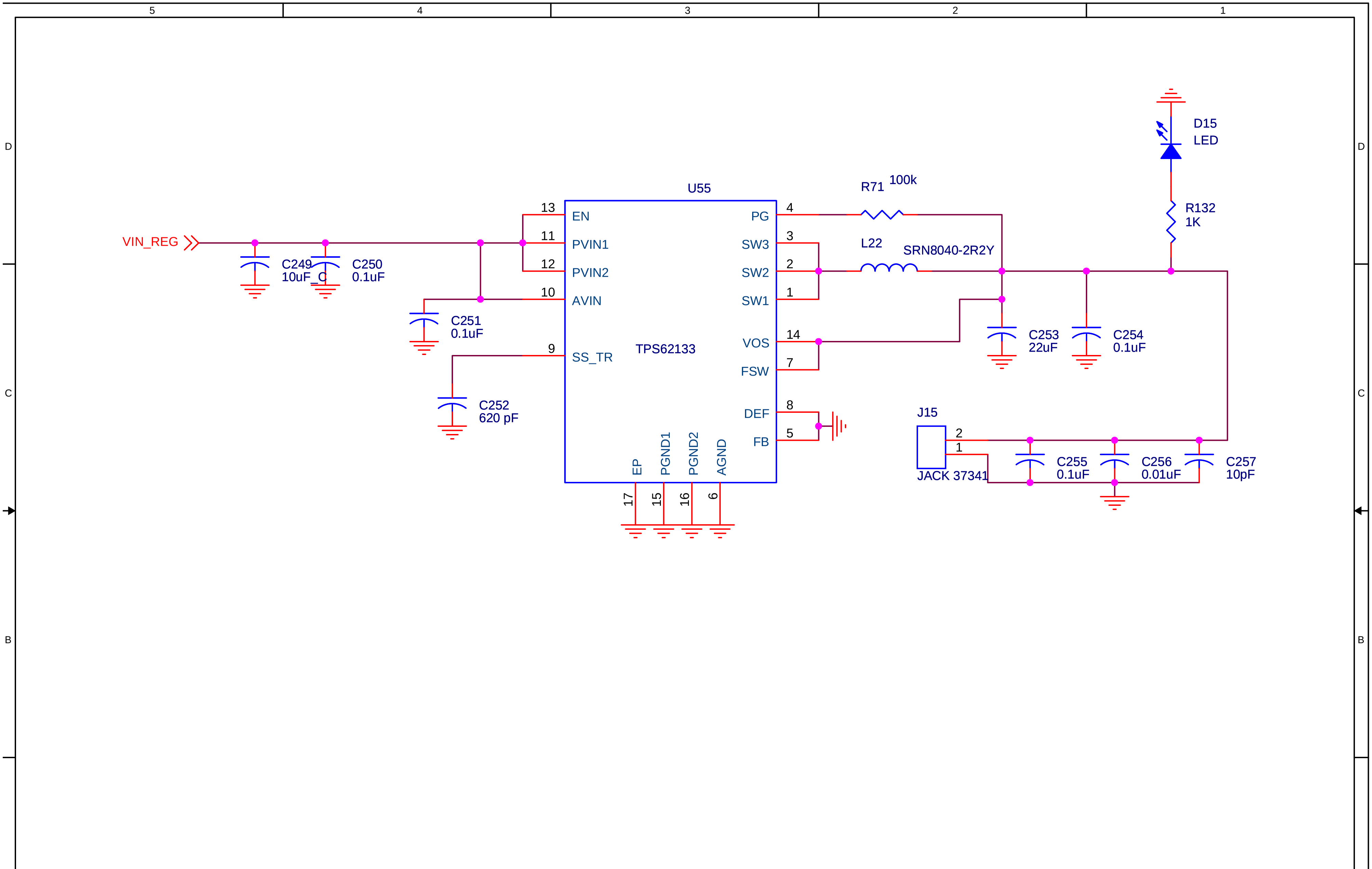
Title: **Transmit_1 Power Amp**

Size	Document Number	Rev
B		

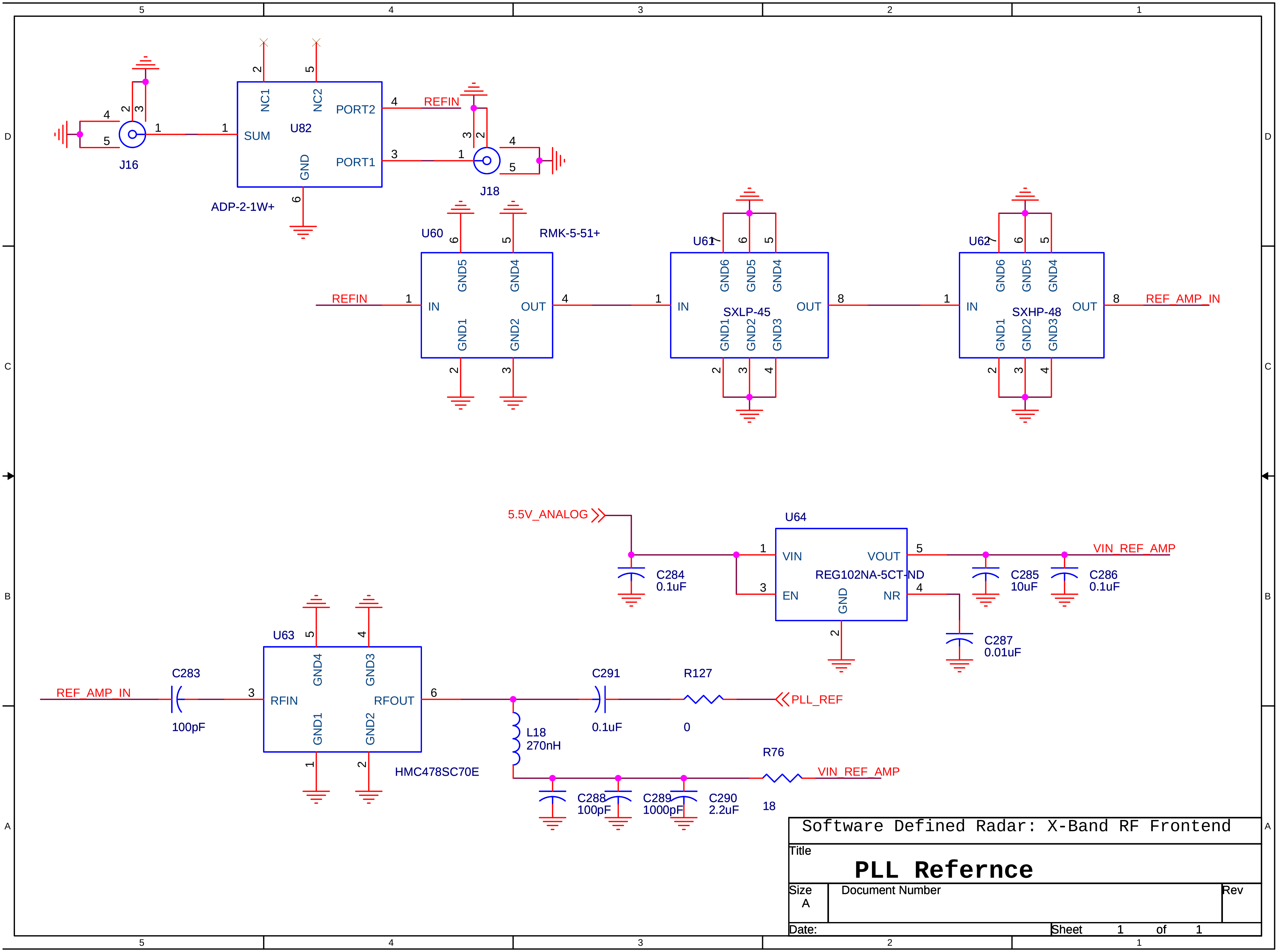
Date: Sheet 1 of 1



Software Defined Radar: X-Band RF Frontend		
Title: **Transmit_2 Power Amp**		
Size: B	Document Number	Rev
Date:	Sheet 1 of 1	



Software Defined Radar: X-Band RF Frontend					
Title **GPS Clock Bias**					
Size A	Document Number				Rev
Date:		Sheet	1	of	1



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ADP-2-1W+
U82
SUM
NC1
NC2
PORT2
PORT1
GND
REFIN
J18
U60
RMK-5-51+
IN
OUT
GND1
GND2
GND4
GND5
U61
SXLP-45
GND1
GND2
GND3
GND4
GND5
GND6
U62
SXHP-48
REF_AMP_IN
5.5V_ANALOG
U64
REG102NA-5CT-ND
VIN
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NR
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C284
0.1uF
C285
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HMC478SC70E
RFIN
RFOUT
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Title
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Size
A
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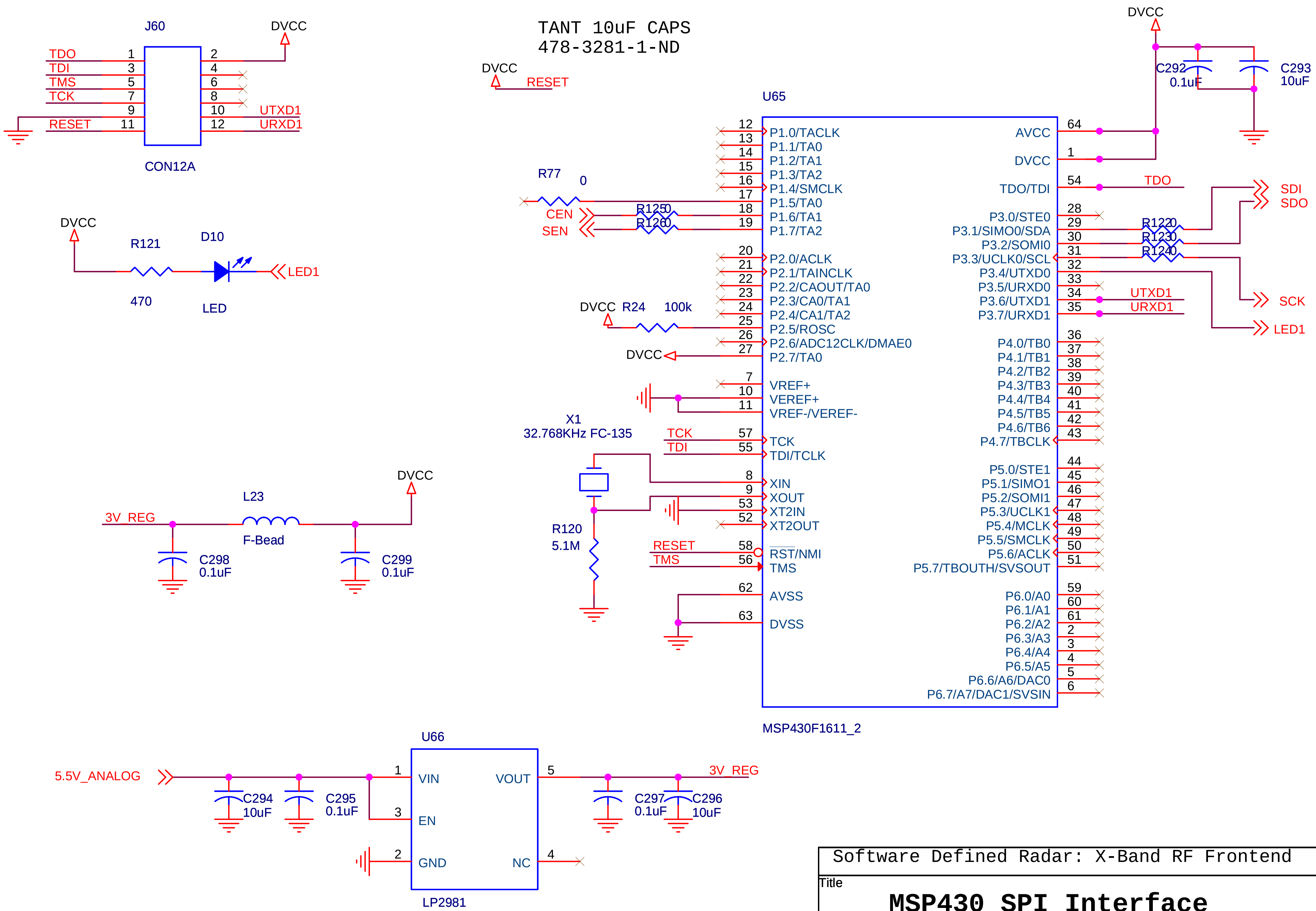
Date:
Sheet 1 of 1



Software Defined Radar: X-Band RF Frontend

Title
MSP430 SPI Interface

Size	Document Number	Rev
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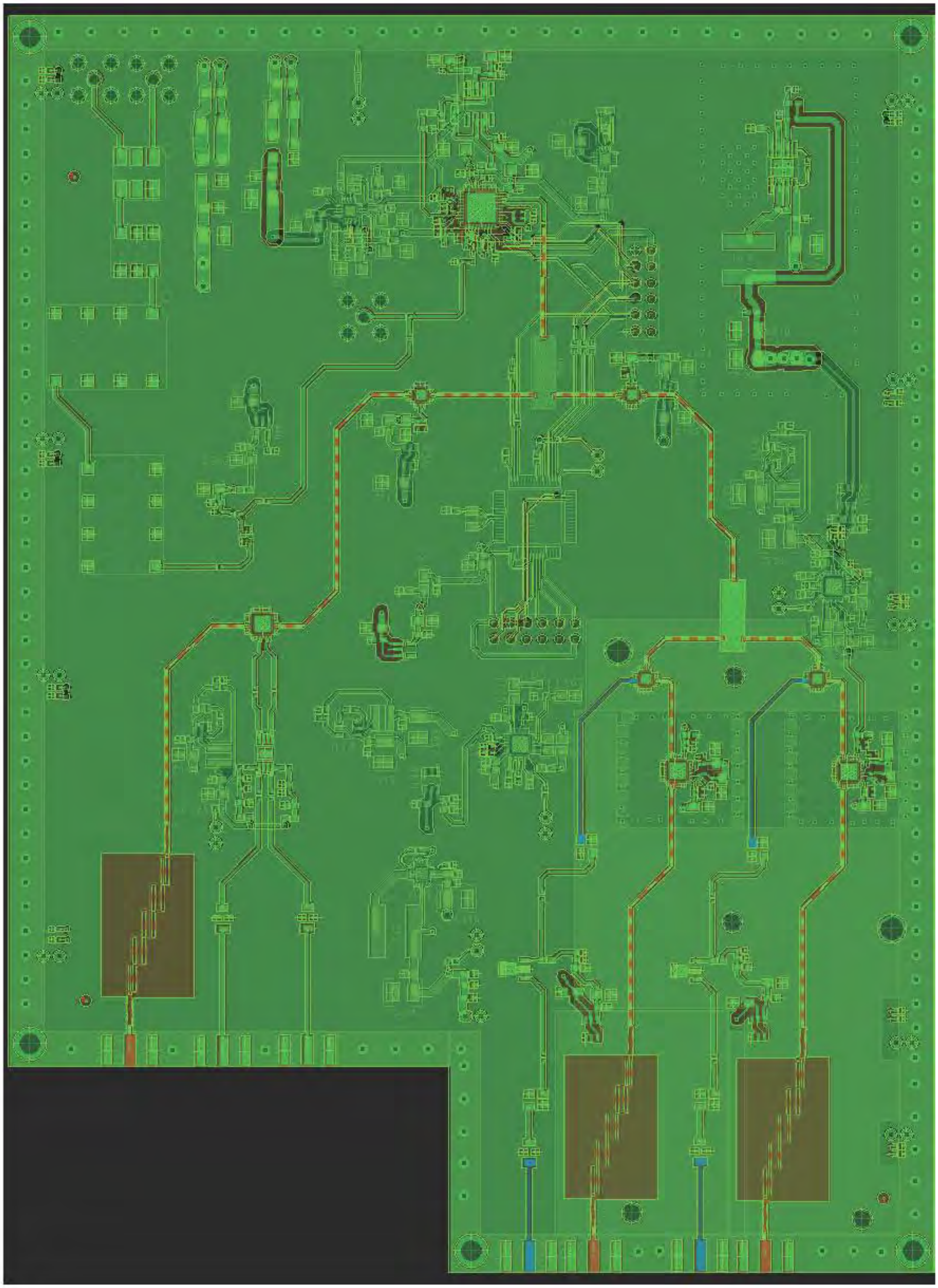
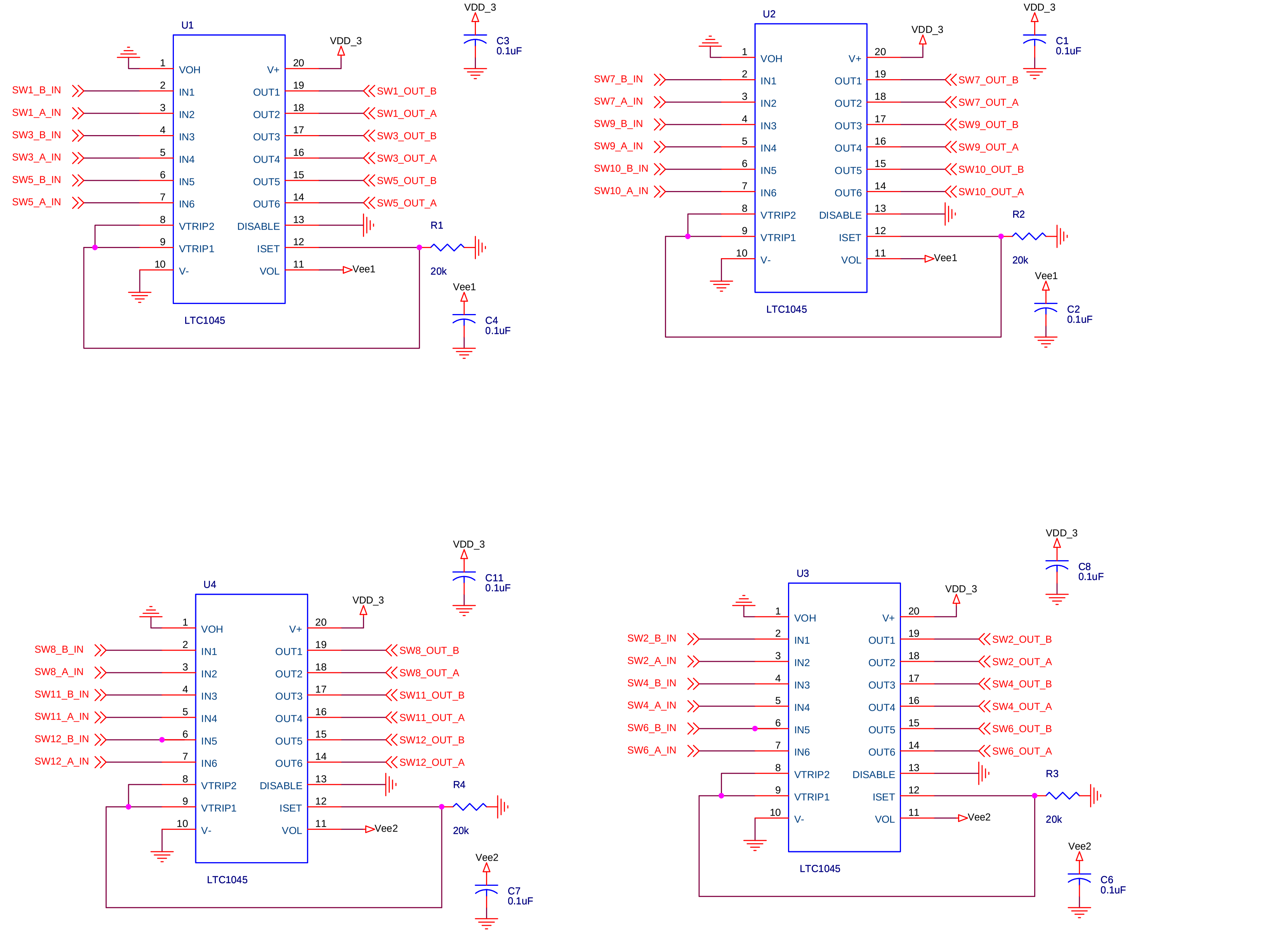
Date: Sheet 1 of 1



Appendix B Schematics for MIMO Antenna Switching Matrix

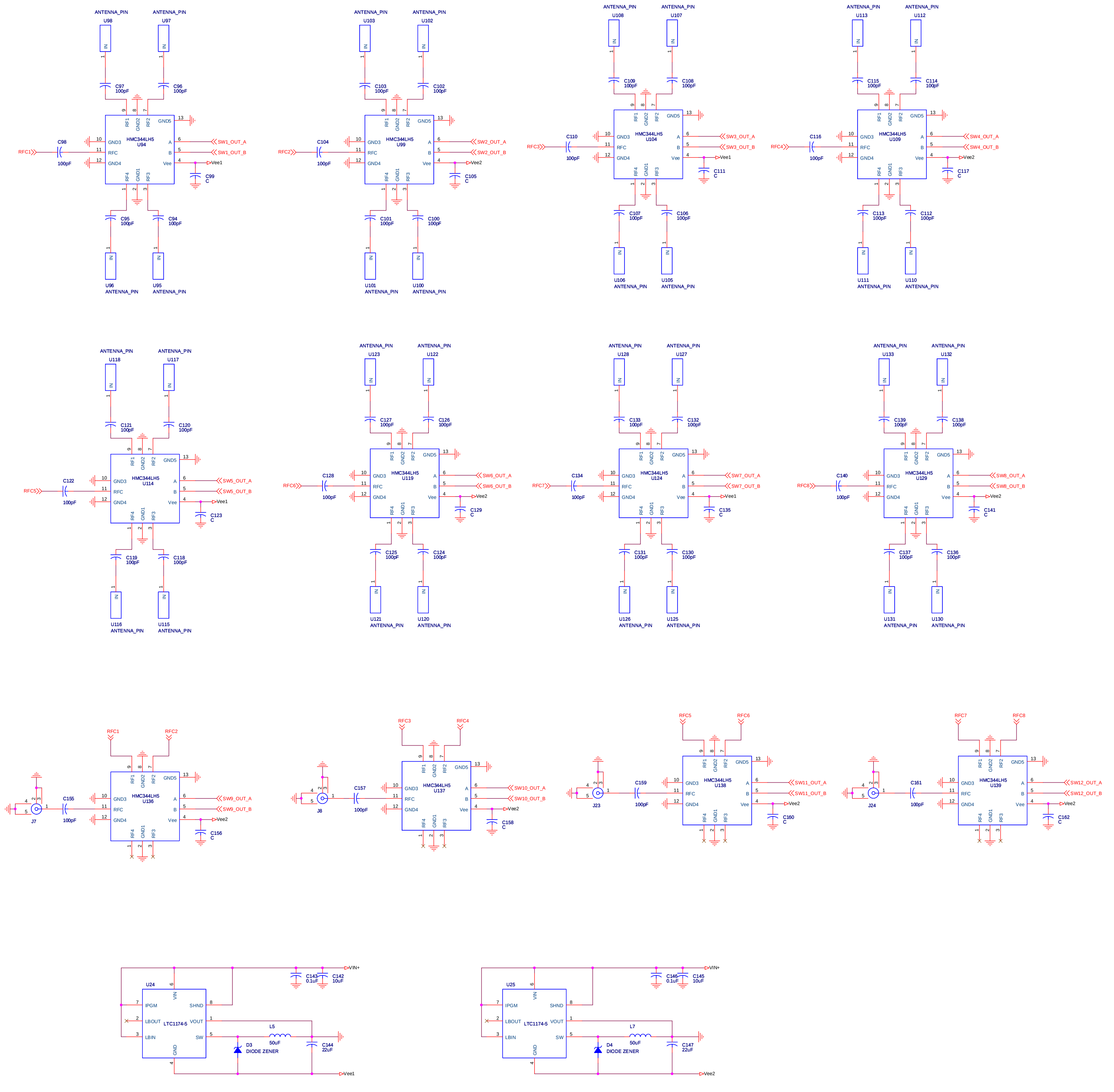


MIMO Radar Antenna Array

Title

Logic Translator/ Level Shifter

Size	Document Number	Rev
Date:	Sheet 1 of 1	

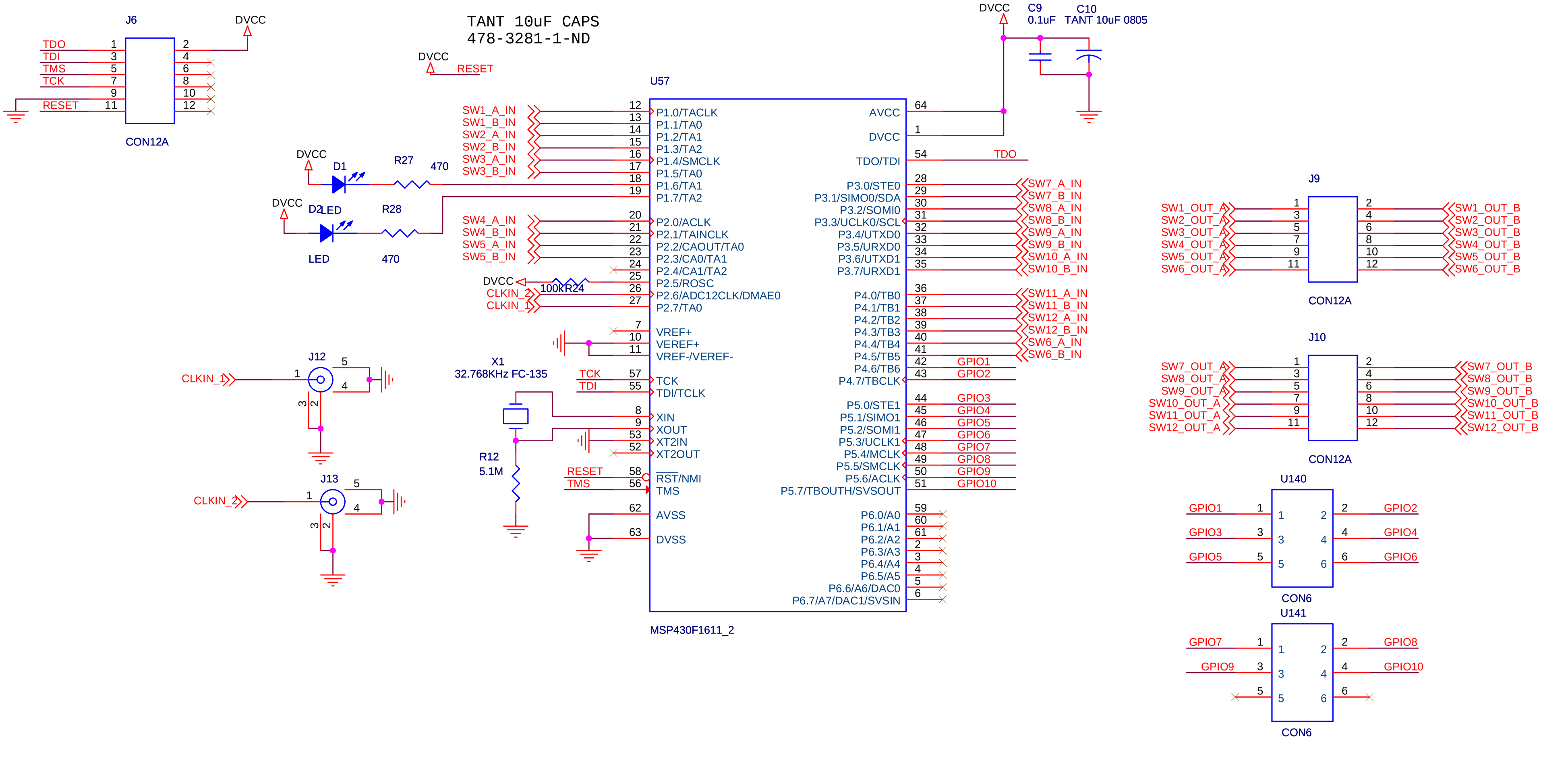


MIMO Radar Antenna Array

Title

X-Band SP4T switches and Bias

Size	Document Number	Rev
Date:	Sheet 1 of 1	

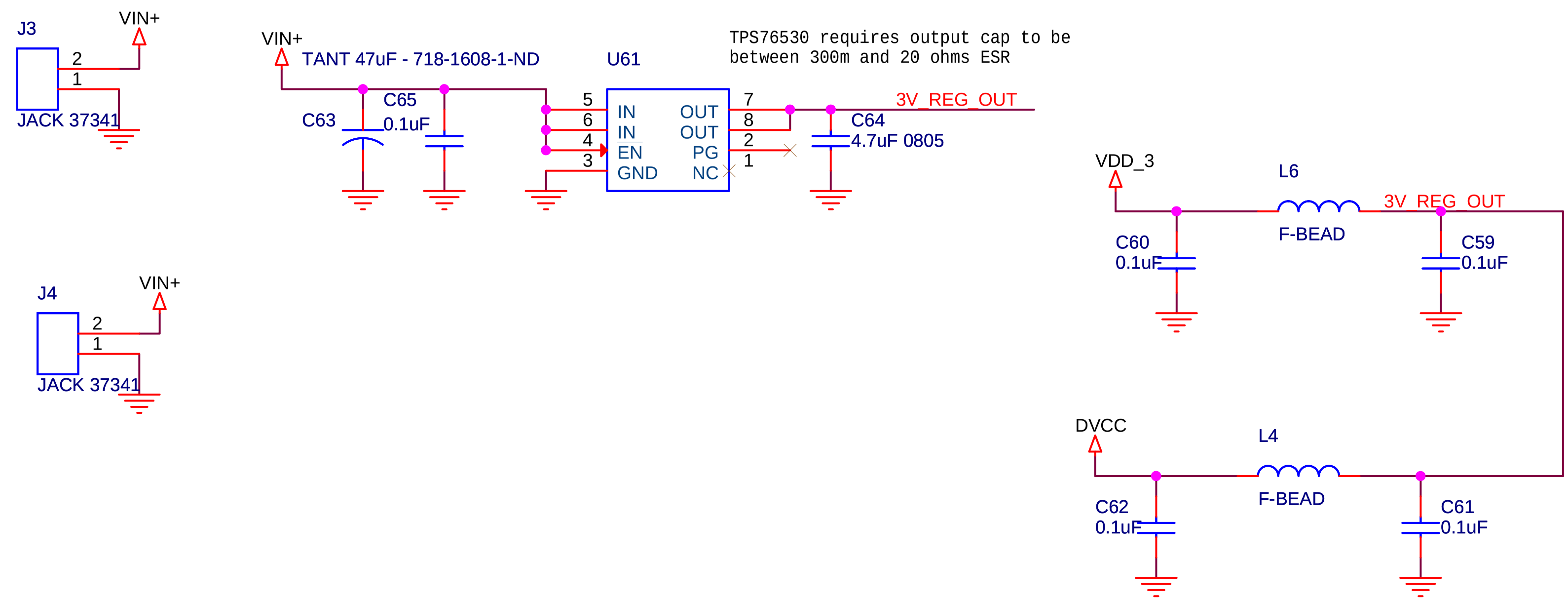


MIMO Radar Antenna Array

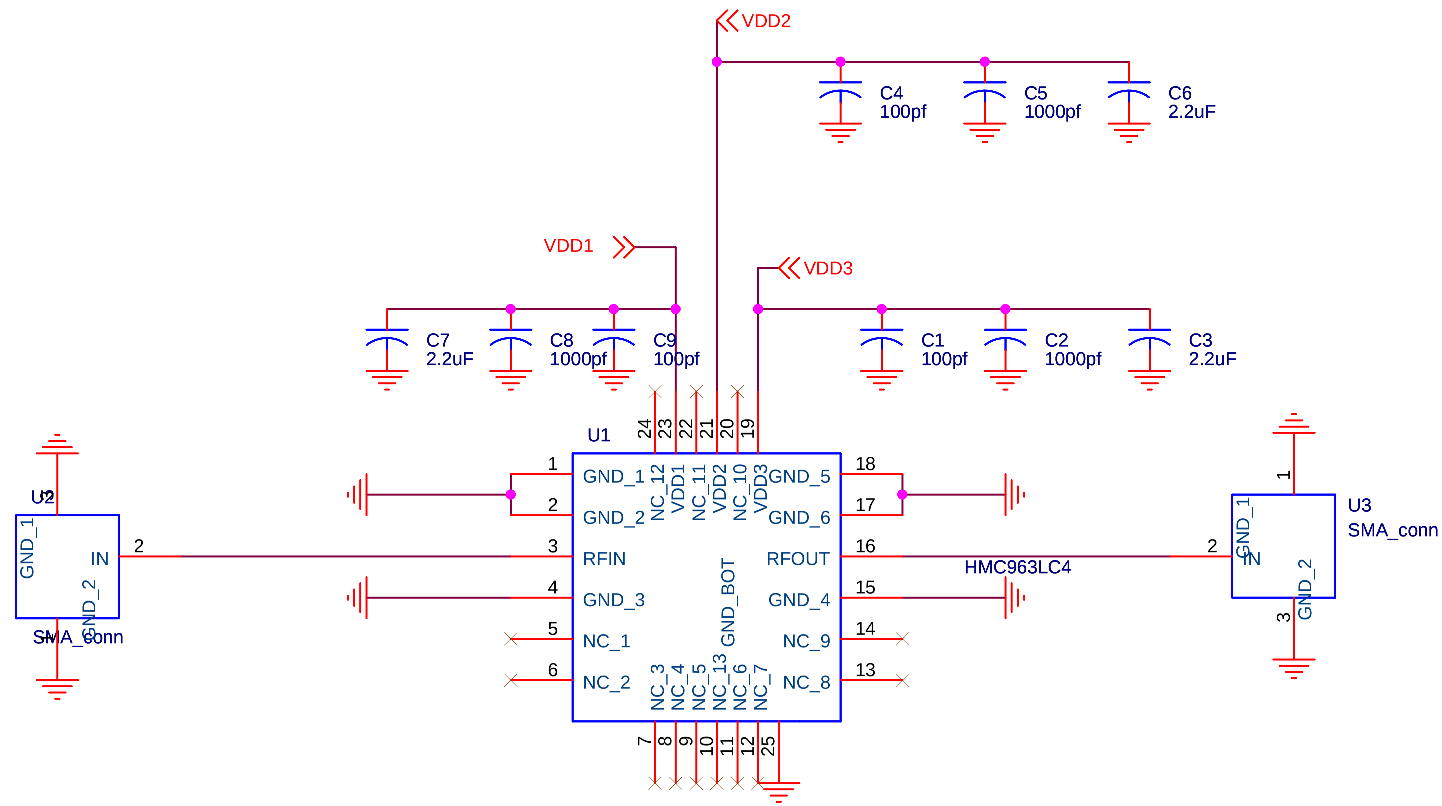
Title
MSP430 MCU with Controll lines

Size | Document Number | Rev

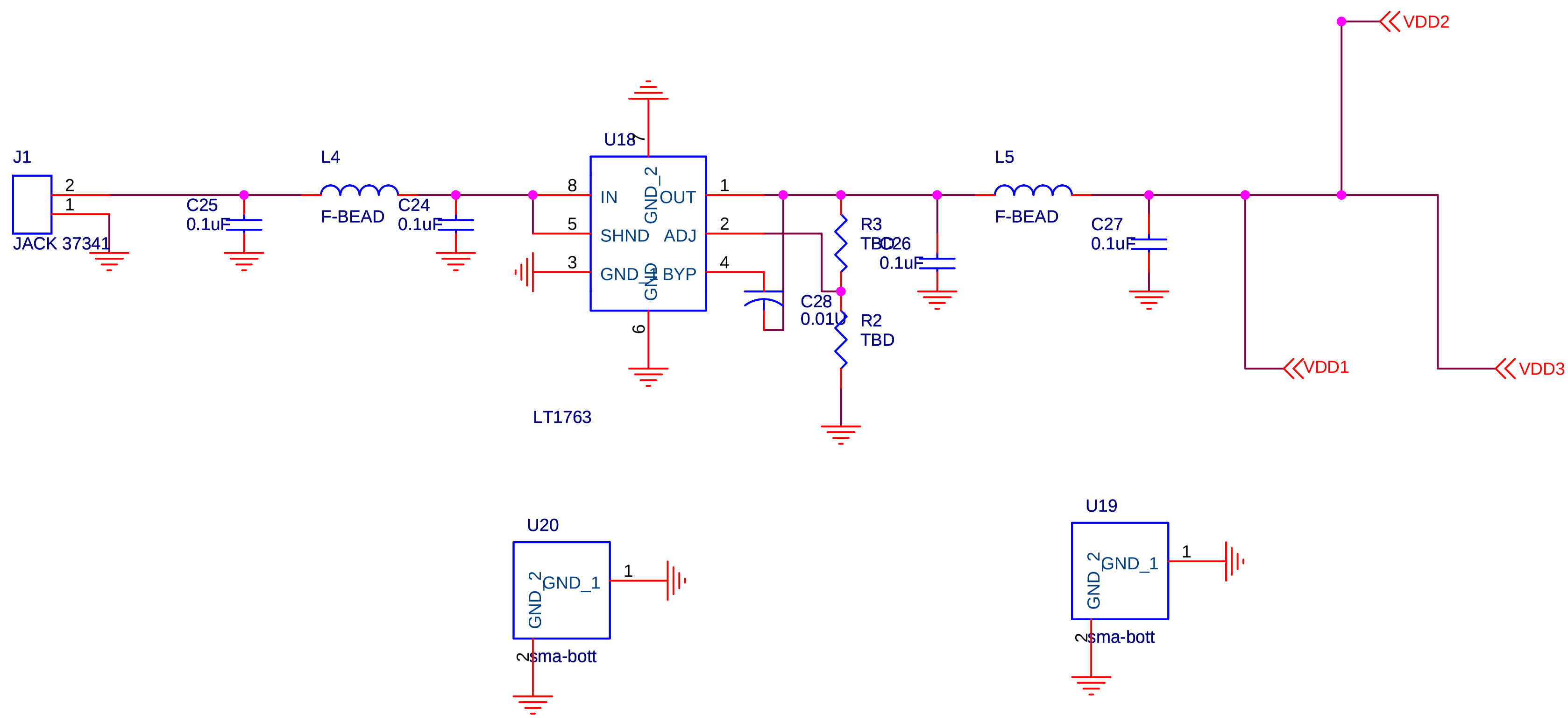
Date: | Sheet 1 of 1



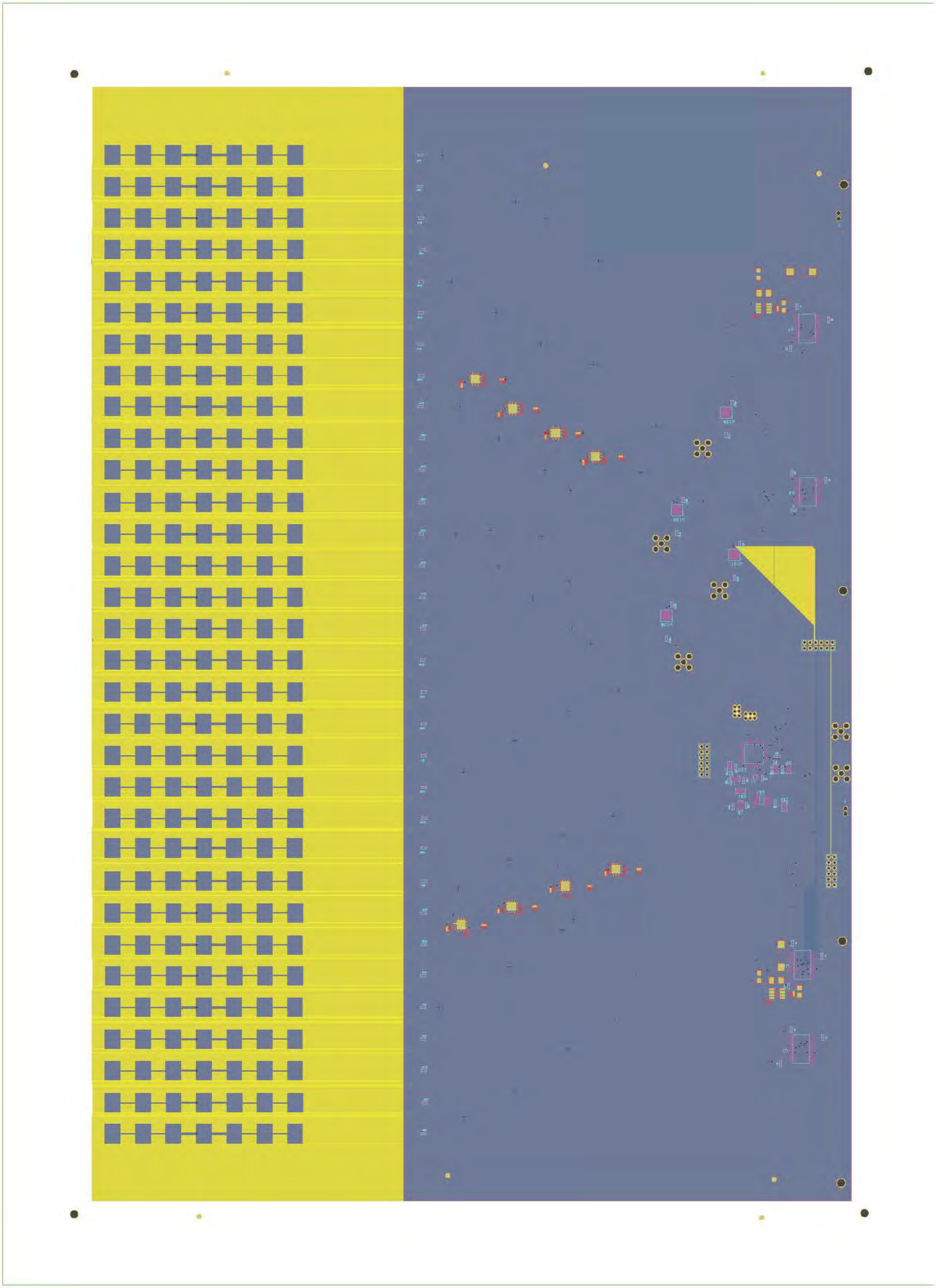
MIMO Radar Antenna Array			
Title: **MSP430 Bias**			
Size: A	Document Number		Rev
Date:		Sheet 1 of 1	

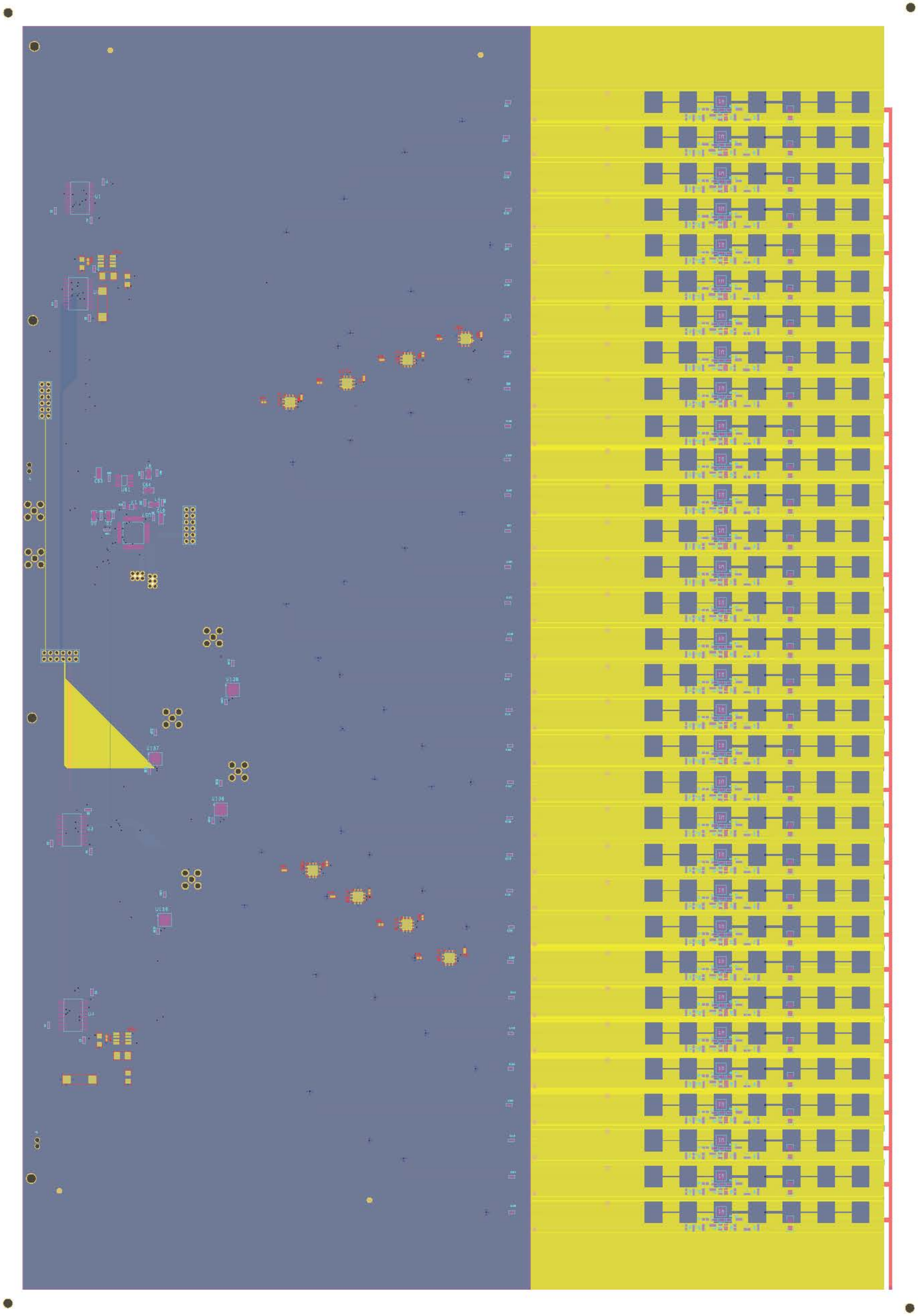


MIMO Radar Antenna Array		
Title: **X-Band LNA**		
Size: A	Document Number	Rev
Date:	Sheet 1 of 1	



MIMO Radar Antenna Array		
Title: **LNA Bias**		
Size: A	Document Number	Rev
Date:	Sheet 1 of 1	





References

[1] E.Fishler, A. Haimovich, R. Blum, L. Cimini, D. Chizhik, and R. Valenzuela *Spatial diversity in radars-models and detection performance* IEEE Transactions on Acoustics, Speech, and Signal Processing, vol. 54, no. 3, pp. 823–838, March 2006.

[2] E. Fishler, A. Haimovich, R. Blum, L. Cimini, D. Chizhik, and R. Valenzuela *Performance of MIMO radar systems: advantages of angular diversity* Conference Record of the Thirty-Eighth Asilomar Conference on Signals, Systems and Computers vol. 1, pp. 305–309, Nov. 2004

[3] N. H. Lehmann, A. M. Haimovich, R. S. Blum, and L. Cimin *High resolution capabilities of MIMO radar* Fortieth Asilomar Conference on Signals, Systems and Computers, pp. 25–30, Oct. Nov. 2006

[4] E. Fishler, A. Haimovich, R. Blum, D. Chizhik, L. Cimini, and R. Valenzuela *MIMO radar: an idea whose time has come* Proceedings of the IEEE Radar Conference. pp. 71–78, Apr. 2004.

[5] C.W. Rossler, E.Ertin, and R.L. Moses *A software defined radar system for joint communication and sensing* IEEE Radar Conference (RADAR), pp.1050–1055, 23-27 May 2011.

[6] Mark T. Frankford, Ninoslav Majurec, and Joel T. Johnson *Software-Defined Radar for MIMO and Adaptive Waveform Application* IEEE Radar Conference, pp.724–728, 10-14 May 2010 .

[7] Jason Yu, Matthew Reynolds, Jeffrey Krolik *An Indoor S-band Radar Receive Array Testbed* IEEE Radar Conference, pp.712–717, 10-14 May 2010.

[8] M. R. Bell *Information theory and radar waveform design* IEEE Transactions on Information Theory, vol. 39, no. 5, pp. 1578–1597, Sep 1993.

[9] J. R. Guerci and S. U. Pillai *Theory and application of optimum transmit-receive radar* IEEE International Radar Conference, pp. 705–710, 2000.

[10] S. Baskar and E. Ertin *A software defined radar platform for waveform adaptive MIMO radar research* IEEE International Radar Conference, 2015.